Ballisticians in War and Peace

Volume I

A History of the United States Army Ballistic Research Laboratories 1914 - 1956

Aberdeen Proving Ground, Maryland

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The United States Army
Ballistic Research Laboratories

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Special Assistant to Director

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THE ARMY'S ORGANIZATION FOR BALLISTIC RESEARCH

During the first year of U.S. involvement in World War I, the Army's ballistic problems were handled by Captain E. M. Ayer, Lieutenant R. H. Kent, and Lieutenant S. W. Alexander in the Artillery Ammunition Section of the Gun Division, Office, Chief of Ordnance (OCO). In addition to other duties, this group planned range firings of new cannon, supervised the ballistic firings conducted at Sandy Hook Proving Ground, computed firing tables, and compiled the first complete table of the Army's cannon and ammunition characteristics.

As the war went on, the demand for firing tables and other ballistic data increased so rapidly that the Chief of Ordnance found it necessary to set up a special organization to carry on this work. On April 6, 1918 he created a Ballistics Branch in his Office.

The first Head of the new branch was Major F. B. Moulton, who in civilian life had been Professor of Astronomy at the University of Chicago. Major Moulton reported directly to the Chief of Ordnance, and under his direction the Ballistics Branch expanded rapidly, laying much of the groundwork for the theoretical investigations and experiments by which the science of ballistics was to be advanced in the next two decades. In addition to the ballisticians already on duty, a number of well-known scientists were added to the staff so that the required work could be done thoroughly and without delay. By this time practically all of the test firings and experimental work were done at Aberdeen Proving Ground.

In many respects the transfer of most of the Ordnance Department's test-firing facilities from Sandy Hook, New Jersey, to Aberdeen, Maryland, begun at the end of 1917, was as significant to the Army's subsequent work in ballistics as was the establishment of the Ballistics Branch in OCO. Until World War I Sandy Hook had been used for the test firings, but it was inadequate because its longest land firing range was less than four miles and the number of firing positions was very limited. The outbreak of war in Europe and the growing danger of U.S. involvement showed that the facilities and available space at Sandy Hook would not accommodate the enormous amount of test work accompanying the expansion of the Ordnance program. Accordingly, a board of officers was appointed to select the site for a new proving ground, and they reported in favor of the area along the Chesapeake Bay between Swan Creek and Gunpowder River near Aberdeen.

On August 6, 1917, Congress, acting on the board's report, authorized the Ordnance Department to establish Aberdeen Proving Ground as the test facility. Construction began before the month ended, and on January 2, 1918 the first test round was fired. Thereafter, almost all of the Department's acceptance and test firings were conducted at Aberdeen; the firings of only a few seacoast guns were continued at Sandy Hook. Equipment and personnel were moved from Sandy Hook to Aberdeen as rapidly as possible.

Nine principal divisions were set up for the newly-established proving ground, and ballistic work was assigned to the Range Firing, Development, and Instrument Sections of the Proof Department. The Range Firing Section contributed most directly to the advancement of ballistics, although much of the work of the two other sections promoted areas of inquiry followed up in the period between the wars.

The Range Firing Section, under Major Oswald Veblen, prepared all firing tables (at that time called range tables), made mathematical analyses of ballistic problems, and conducted experiments to obtain information for increasing the range and accuracy of projectiles.

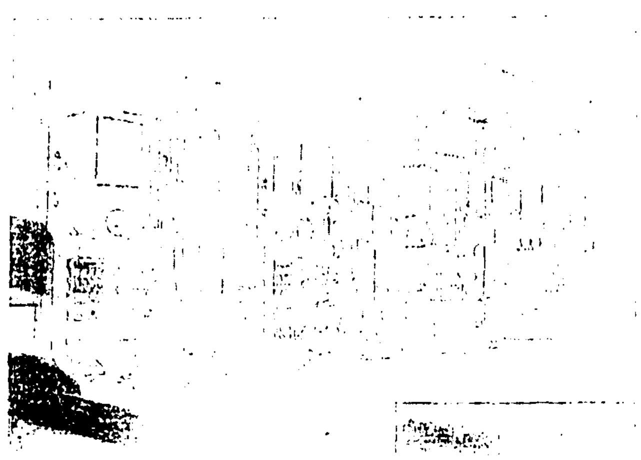
The Development Section, headed by Captain A. L. Loomis, assisted in the development of fuzes, boosters, explosives, and trench warfare materiel, developed instruments for use by the Instrument Section, and tested all guns, carriages, tractors, and tanks developed by the Ordnance Department.

The Instrument Section measured projectile velocities and powder pressures and did all the photographic work, surveying, and drafting the Proof Department required. In addition, its personnel developed and improved pressure gauges, devices to measure recoil, star gauges, and high-speed cameras for ballistic work. They also maintained records of gun barrel erosion.

This organization of the Proof Department for ballistic research and development, put into effect at the beginning of 1918, was continued without major change until the middle of 1922.

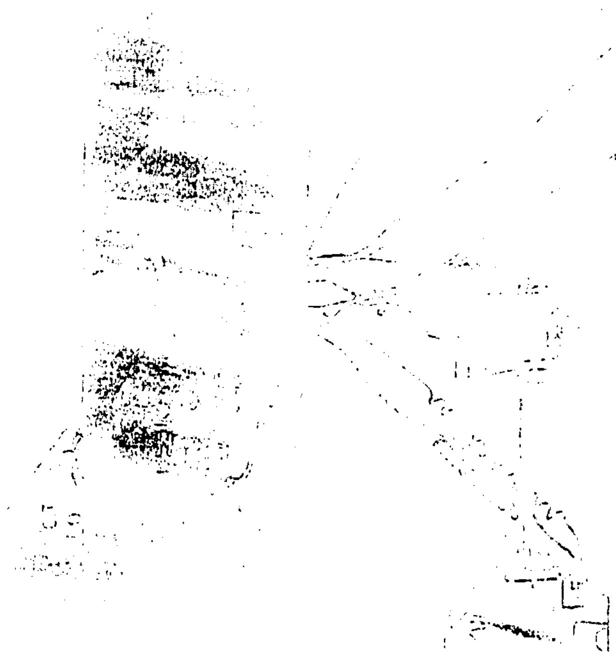
DEVELOPMENT OF THE ABERDEEN CHRONOGRAPH

Possibly the most outstanding single contribution of Aberdeen Proving Ground to the advancement of ballistic analysis in 1918 was the development of the Aberdeen chronograph. Like all empirical sciences, ballistics depends on precision instruments and computing devices for obtaining and working the data essential to its continued progress. Only when instruments for accurately measuring muzzle velocity are available, for example, is it possible to distinguish the effects of interior and exterior ballistics on the accuracy of a gun-ammunition combination. Moreover, it is necessary for such instruments to be available in sufficient numbers so that they can be used where and when needed. Among the instruments on which ballistics depended in World War I were star gauges for measuring gun bores, gauges for measuring chamber pressures, chronographs and other devices for determining projectile velocities, meteorological instruments, transits, and azimuth finders.



Boulengé Chronograph

The greatest difficulty encountered in the early proof work at Aberdeen was an insufficient supply of accurate chronographs for measuring muzzle and striking velocities. Several Boulengé chronographs were available, but there were not enough to accomplish the necessary work. Moreover, the device was a laboratory instrument whose accuracy depended on its being mounted on a vibration-proof pier. Developed in 1867, the Boulengé chronograph was still the standard device used in most countries for determining projectile velocity in 1917, but its limitations were becoming increasingly evident. Accordingly, Captain Loomis of the Development Section, with the assistance of Dr. Paul E. Klopsteg of the National Bureau of Standards, developed a new chronograph that was both usable on a firing range and less expensive than the Boulengé chronograph to manufacture. It became known as the Aberdeen chronograph.



Aberdeen Chronograph

The Aberdeen differed from the Boulengé chronograph principally in that it used a projectile to complete rather than break an electric circuit to measure time of flight. Its design was completed in March 1918 and at once proved very satisfactory. The new instrument had approximately the same accuracy of the Boulengé chronograph, but it also had the great advantage of being portable, producing accurate velocity measurements wherever electric power was available. Designed especially to measure the velocities of small arms projectiles, it was particularly reliable in determining the striking velocities of bullets.

Although the Aberdeen chronograph has been improved since it was introduced in early 1918, its basic design has remained unchanged.

EXTERIOR BALLISTICS

Exterior ballistics — that part of the science dealing with the behavior of projectiles in flight — underwent a major revolution during World War I. In 1914, when the conflict opened in Europe, the problems that confronted the exterior ballistician were for the most part associated with flat-trajectory fire. Between 1914 and 1918, however, the tactics of land warfare were radically changed by the increasing dependence on artillery barrages in which field pieces were fired at relatively high elevations over the heads of their own infantry. The type of fire required by the new tactical doctrine compelled a general re-evaluation of exterior ballistics. Some of the older theories and practices were found to be incorrect when examined in the light of the new conditions. Others had to be modified. A projectile continued to be regarded as a body; the relative motion of its parts could be ignored. The only resistance factors considered as affecting a projectile in flight continued to be gravity and the air resistance; many other basic premises remained unchanged for use in ballistic computations. Nevertheless, the complexity of the new problems created by the general use of high-angle fire gave enormous impetus to research in exterior ballistics until World War II, when the introduction of new weapons again accentuated the need for intensive investigations of still greater scope.

Computation of Trajectories. Before World War I trajectories had been computed in all countries by the methods developed by the Italian ballistician, Siacci, whose data had come from the Krupp experiments at Meppen, Germany. The data were reduced to equations by General Mayevski, of Russia. Siacci had succeeded in developing tables which, despite their small size, could be used to solve the entire ballistic problem of fire from guns not elevated above 15 degrees. Within this elevation limit, the results were accurate to ranges up to approximately 24,000 yards. However, the demands made on artillery by the general introduction of barrage fire in World War I created new ballistic problems which could not be solved by Siacci's method. The Ingalls ballistic tables (US Artillery Circular M, revised in 1914), based on the Siacci system, were no longer usable.

The two new problems introduced into trajectory computation were the result of high-angle fire and the need for greater accuracy in the computations themselves. New ballistic tables were required to take into account the effect of change in air density with altitude on the flight of projectiles. The use of the moving barrage and the need for rapid and effective counterbattery fire required that artillery fire be directed with greater accuracy than had ever been contemplated.

A special (and extreme) form of the problem of high-angle fire was created by the introduction of aircraft as a military weapon. The antiaircraft artillery developed to defeat enemy aircraft had to be able to fire at all elevations up to 80 or 85 degrees. Moreover, the projectiles fired had to be detonated by time fuzes, which meant that their position at any moment in their flight had to be known. Finally, the speed of even the World War I aircraft was sufficient so that all adjustments for firing had to be made in a few seconds. The Siacci method and the Ingalls ballistic tables could not meet the new requirements.

The European countries engaged in World War I had encountered these problems at the beginning of trench warfare in late 1914 and again when aircraft were introduced as a major weapon in early 1915. As a result, they promptly developed new methods for computing projectile trajectories. Practically all of these methods were variations of the French *short-arc* method, which calculated any given trajectory as a series of successive arcs rather than as a continuous line. Computation by the short-arc method was laborious and time-consuming, but it made possible corrections for varying air density and certain other factors affecting a projectile's flight. Although corrections could be made for wind effects by this method, such effects were actually treated as differential variations. For some time the short-arc method was the only satisfactory means to prepare ballistic and firing tables required for high-angle fire.

BALLISTICS DURING WORLD WAR I

In 1918 Major Moulton developed a more flexible and less complicated method for computing ballistic tables. Usually referred to as the numerical integration system, it was essentially a valuable simplification of the short-arc method. By its use, eighty trajectories were computed before the end of the war. They included those for the 2.95-inch mountain gun, the 75-mm and 3-inch antiaircraft guns, the Model 1894 75-mm field gun, the 4.7-inch gun, the GPF 155-mm gun, the Mark VI 8-inch howitzer, and the 8-inch and 10-inch seacoast guns. The results of these computations were employed in preparing firing tables for these weapons.

A few years later, Captain A. A. Bennet of the Ballistics Branch began to compile fundamental ballistic tables that could be used for all calibers of artillery weapons. The task was monumental; the third and final volume of tables was not published until 1936.

Compilation of Firing Tables. Information about projectile trajectories, however accurately computed, had little direct value for the artilleryman in the field. What he needed was a firing table that showed the range to be expected for each gun and howitzer when it fired a specific projectile with a given propelling charge at any selected angle of elevation. The table also had to indicate the corrections to be applied for variations in atmospheric temperature, air density, wind, angle of site, weight of projectile, muzzle velocity, and compensation for drift, and in some cases, for the rotation of the earth.

In wartime, firing tables must be prepared and sent to the field as rapidly as possible because, without the information, artillery is relatively useless. Consequently, in World War I much of the time of the Proof Department, Aberdeen Proving Ground, was devoted to firing table work.

The greater part of the load was carried by the Range Firing Section, whose highly trained personnel worked most competently under the direction of Major Veblen. The section was divided into Firing, Observation, Computation, Antiaircraft, and Meteorological Units. The last of these units originated from the outgrowth of a meteorological detachment that was sent to Aberdeen by the Signal Corps in March 1918 to provide weather data for the firing tables being prepared. Measurements of wind velocity, air temperature, and air density were taken several times daily to an average altitude of 15,000 feet, and some readings were made to altitudes up to 52,000 feet. This was pioneering work; much of it was being done for the first time in this country.

The volume of work accomplished by the Range Firing Section in the relatively short time between its establishment and the end of the war was indicated by its reports on more than 10,000 shots fired to obtain range data and its compilation of more than thirty firing tables for United States Army weapons. In order to get the range data it needed, this section, with the assistance of the United States Coast & Geodetic Survey, erected sixteen observation towers (only four of which were used in plotting at any one time), over a distance of thirty miles along the shore of the Chesapeake Bay. Observers in these towers were 100 feet above water level. They spotted the splashes made by projectiles hitting the water and reported their observations to both the gun crews and computers by a wireless system installed by the Signal Corps. Replaced by a wire telephone system in the latter part of 1918, this wireless system was nevertheless the first of its type to be used for this purpose. A two-way radio-telephone system is now used in the towers and patrol boats. The spotting system is still used for measuring ranges for firing table purposes at Aberdeen Proving Ground.

To perform the antiaircraft phase of the firing table work, Lieutenant P. L. Alger was transferred to Aberdeen from Sandy Hook Proving Ground in May 1918, and Captain F. W. Loomis of the Ballistics Branch, OCO, who had just returned from a tour of duty in England, was assigned to temporary duty with the Range Firing Section, Aberdeen Proving Ground. Captain Loomis brought with him a mirror position finder developed in Great Britain for spotting bursts of antiaircraft shrapnel. With the help of a well-organized group of observers and computers, the Range Firing Section prepared four firing tables for antiaircraft guns; they were the first accurate tables of this type prepared in the United States.

Although the preparation of firing tables was routine and generally followed the methods used in other countries, the contributions of Dr. G. A.

Bliss and Dr. T. H. Gronwall were invaluable. While a member of the Range Firing Section during the war, Dr. Bliss developed the adjoint system of differential equations for determining variations in range resulting from changes in such conditions as air density and initial velocity. Dr. Gronwall, who also was a member of the Range Firing Section, elaborated this method to determine the effects of such variations on time of flight and the maximum ordinate and to develop formulas by which compensations for vertical wind could be made.

Studies of Projectile Design. Firings conducted to obtain range data frequently demonstrated that projectiles had greater or shorter ranges than expected on the basis of theoretical analysis, or that their dispersion did not conform to expected patterns. Several theories were advanced to explain these phenomena; most of them emphasized either the shape or stability of the projectile. Factual confirmation of the theoretical explanations was needed. Accordingly, the Range Firing Section was directed to conduct theoretical and experimental investigations to supplement the research conducted by the Ballistics Branch, OCO, to determine the effects of the various forces that act on the range and accuracy of a projectile.

In the past, in order to increase range and accuracy, a projectile was fired with a known powder charge. The range and dispersion were noted, the projectile's design modified, and the procedure repeated. This was time-consuming and expensive, and the results were frequently inconsistent. As an alternative it was argued that, if the laws governing the resistance of air to a projectile could be accurately determined, it would be possible to calculate both range and dispersion within very narrow limits. For this purpose, a number of proving ground and wind tunnel experiments were required, so a program to conduct these tests was planned.

Projectile Retardation Studies. Studies made before 1914 identified the forces that an air stream of a given density, velocity, and pressure exerts on a projectile having a square base and blunt ogival nose as it is fired through the air. Also, the law of air resistance, calculated by the French during the period 1866-1898, had been found to hold true for most projectile forms at velocities between 600 and 1,200 fps. This law was used in constructing firing tables before World War I and, to a considerable extent, tables prepared during most of that conflict. However, it proved to be inapplicable to projectiles having a boattail or a long head fired at supersonic velocities, which included many of the newer shot and shell developed for wartime use. Additional information was needed before accurate firing tables could be prepared for modern weapons, and to some extent this information was provided by studies carried out by the combatant countries after 1914. Specifically, the greatest advances were made in evaluating the effects of air density, air temperature, and projectile velocity on the resistance a projectile encounters in flight.

After the U.S. entered the war, the Ballistic Branch of OCO cooperated with the Range Firing Section at Aberdeen in working on this general problem. One of the Branch's contributions was the discovery that the law of squares (which states that a projectile's retardation in flight as the result of air resistance is roughly proportional to the square of its velocity) did not apply to either transonic or supersonic velocities. At velocities between 700 and 1,700 fps the Gavré air resistance increased much more rapidly than the square of the velocity; at higher velocities, air resistance increased less rapidly than the law of squares had indicated.

It was also found that atmospheric temperature affected a projectile's velocity because it was one of the factors on which atmospheric density depended, and because the retardation rate varied with it.

Finally, it was determined theoretically that the resistance air offered to a projectile was directly proportional to the air's density.

Boattail Studies. The practice of boattailing projectiles, introduced by the French early in World War I, had already produced noteworthy results by the time the U.S. entered the war; both range and accuracy were measurably increased by slightly streamlining a projectile's base section. After Aberdeen Proving Ground was established, Major Veblen began a series of boattailing experiments, most of which had excellent results.

The first projectile so modified (in May 1918) had a greater range than its unmodified counterpart. In rapid order the Mk I 4.7-inch HE shell, the Mk II 6-inch HE shell, 155-mm shrapnel, and the Mk I 8-inch HE shell were similarly treated. The results obtained with boattailed shell on the firing range were confirmed and in part explained by open-throat wind-tunnel experiments conducted jointly by the Ordnance Department and the National Bureau of Standards at Lynn, Massachusetts. For this work, Colonel William H. Tschappat, Commanding Officer of Aberdeen Proving Ground, secured the services of Dr. Briggs (later the Director, National Bureau of Standards), Dr. Buckingham of the National Bureau of Standards, Dr. G. F. Hull of Dartmouth University, and Dr. H. L. Dryden of the National Bureau of Standards, Director of the National Advisory Committee for Aeronautics (later a member of the Scientific Advisory Committee, BRL). To obtain the necessary information, a projectile of given design and dimensions was placed in air streams of various velocities, with provisions made for measuring air resistance. It was found that the forces which retarded a shell in flight decreased in effect until the angle of boattailing was in the range of 5 to 9 degrees. No best form for any given type of projectile could be determined before the war ended, but the value of boattailing as a design feature of artillery projectiles was clearly demonstrated.

Rotating Band Experiments. Another approach to increasing range and accuracy by changes in projectile design was made by experimenting with the form and position of rotating bands. This work appears to have begun at Sandy Hook Proving Ground, where Lieutenant Alger, among others, noted the great dispersion of the Mk II 6-inch HE shell when fired from the 6-inch seacoast gun. When measured at Sandy Hook and, later in 1918, at Aberdeen Proving Ground, dispersion was found to be as great as 10 percent of the range, rendering this gun-ammunition combination practically useless. Experiments demonstrated that it was not caused by instability of the gun's mount, and additional investigations to account for it were promptly initiated.

Projectiles were fired through cardboard screens to obtain information about their behavior near the muzzle of the 6-inch gun. The holes the projectiles made in these screens were ragged and, on the average, from 6.25 to 6.75 inches in diameter, considerably larger than the diameter of the shell. On investigation, it was found that the copper of the rotating bands had flowed back 0.5 to 0.75 inch, expanding in the process, and had flared out under the pressure exerted by the powder gases as the projectiles left the gun. In some instances portions of the expanded bands had broken off. These phenomena were explained when it was found that the rotating bands of these shell contained too much copper and had a projection or lip on their rearward edge. The resulting expansion of these bands increased the over-all diameter of the projectiles by approximately 20 percent, causing a corresponding increase in retardation by the air and a resulting reduction in range. The extraordinary dispersion was caused in large part by the irregularities of the expanded bands.

To eliminate these defects, the lips of the rotating bands for the Mk II 6-inch HE shell were machined off and cannelures were made directly behind the bands to stop the rearward flow of copper. Shell fitted with these modified bands, when fired through cardboard screens, produced normal holes and had a remarkable increase in both range and accuracy; range was increased by about 25 percent and dispersion was reduced by about 80 percent. As a result, orders were issued for all lips to be removed from rotating bands for shell, whether still in this country or already shipped overseas. Similar experiments conducted with the shell for six other guns and two howitzers confirmed the findings made with the 6-inch HE shell.

On the basis of these experiments with rotating bands and boattailed projectiles, the Range Firing Section designed a shell with a boattailed cylindrical body and a long false ogive, submitted it to the Artillery Ammunition Section of the Gun Division, OCO, and recommended that projectiles of this design be manufactured in the desired calibers. Within a few months the Mk VIII 6-inch HE shell, which closely followed the Range Firing Section's design, was authorized for manufacture. It proved to be very satisfactory.

Although the experiments with rotating bands proved to be significant, it was never concluded that losses in range could be attributed solely to improper bands. Other possible factors, such as a projectile's instability in flight, were given full attention at the same time as the work on boattailing and rotating bands was being conducted.

Projectile Stability Studies. Early in 1918 Major Ayer and Lieutenants Kent and Alexander, of the Artillery Ammunition Section, OCO, designed conical aluminum windshields to be fitted to projectiles of several calibers to increase both their range and accuracy. These windshields were to fit over the normal ogives to change the form of a projectile from ogival to conical and give it greater length. The war ended, before any conclusive results could be obtained from these experiments, but the work was continued after Armistice Day, producing significant progress in the following decade.

Center of Gravity Experiments. The boattailing and rotating band experiments had unquestionably been successful, yet it was impossible to specifically define how each design change had operated to increase range and accuracy. Before such questions could be answered (and answers were necessary before the experience gained could be reduced to general principles applicable to projectile design), additional information was needed. Plans were made by the Ballistics Branch, OCO, to examine thoroughly all the factors involved in the design of a projectile and to determine the extent to which a projectile's performance in flight depended on these factors. Under the direction of Lieutenant Alexander, a number of different projectiles was constructed so that each of the major physical characteristics could be varied at will to determine its relative effect on overall performance. The basic projectile consisted of four parts: cylindrical bodies of different lengths; conical and ogival heads of different lengths; bases of different shapes; and cylinders of different lengths that could be screwed into the threaded interior of the body to change the center of gravity. To determine the effects of pitch of rifling on projectile behavior, the 3.3-inch guns in which these projectiles were to be test-fired were rifled at three different pitches. Here again the war ended before any real progress was made in the investigations. However, the work was continued after Armistice Day, with good results.

INTERIOR BALLISTICS

Interior ballistics — that part of science dealing with the behavior of projectiles from the moment their propelling charges are ignited to the time they leave the muzzle of the cannon — underwent no expansion in World War I comparable to the developments in exterior ballistics. Practically all of the computations made in interior ballistics throughout the war were based on the equations of Captain Le Duc, of the French Army, and the studies carried out in this country were restricted for the most part to obtaining data on propellants needed for immediate solutions to specific problems. No major program of far-reaching influence was initiated. This lack of attention to interior ballistics was largely due to the fact that few new guns were designed during the war. Guns that were developed had no radically new design features — they were merely more powerful than the guns they replaced. For this reason, the work done at Aberdeen Proving Ground in interior ballistics was mostly of a routine character, following generally the program that had been in effect for some time before the U.S. entered the war.

Tests were conducted to determine the maximum muzzle velocities and chamber pressures allowable for specific guns firing different projectiles. Experiments were run to determine the effect of powder temperatures on muzzle velocity, with particular attention paid to confirming the data already at hand.

RELATIONS WITH AMERICAN AND FOREIGN BALLISTIC AGENCIES

Throughout the war the Allied agencies engaged directly or indirectly in ballistic research recognized the need for full cooperation so that the findings of each might be at the disposition of all. The Proof Department of Aberdeen Proving Ground played its full part in such enterprises. In particular, it maintained constant liaison with the Field Artillery and the Coast Artillery, the users of the firing tables prepared at Aberdeen. Close

relations on more theoretical problems were maintained with both the National Bureau of Standards and the National Research Council, as well as with the Naval agencies engaged in ballistic work.

Much valuable assistance was received from the French and the British War Missions, which gave Aberdeen information about new ballistic theories, French and British weapons and ammunition, and enemy ordnance. In return, the results of the experiments with boattailing and rotating bands were promptly transmitted to both Allies, along with copies of papers on ballistic subjects prepared in this country.

In October 1918, Major Veblen and Lieutenant Kent were sent to Europe to study the research and development work carried on by the British, French, and Italian ballisticians. Their comprehensive report could not be published before the end of the war, but it was made available to research groups in this country as soon as possible and proved to be of great assistance in the 1920's. Dr. Veblen's recommendations for the guidance of ballistic research and development agencies in peacetime were of particular significance. He proposed that major emphasis be placed on the design of guns and projectiles to increase their effectiveness, that the advances made in exterior ballistics during World War I be carefully studied and systematically described, that additional ballistic tables be compiled, and that a program be set up to revise the methods and procedures used in interior ballistics. It is interesting to note (and this will be shown in the next two chapters), that these recommendations were followed quite closely in the years after World War I, with good results.

THE ROLE OF THE OFFICE, CHIEF OF ORDNANCE, IN THE PROMOTION OF BALLISTIC RESEARCH

Early in 1919 Major General Clarence C. Williams, Chief of Ordnance, reorganized his Office to meet the new requirements of peacetime operations, giving it a pattern which remained essentially unchanged until after World War II had broken out in Europe. Under his plan the Office, Chief of Ordnance, was organized in four major parts: the General Office, the Manufacturing Service (renamed the Industrial Service in 1939), the Field Service, and the Technical Staff.

All administrative and general supervisory responsibility was vested in the General Office, and operating responsibilities were divided between the Manufacturing and Field Services. The Manufacturing Service designed, developed, produced or procured, and inspected all new Ordnance materiel; administered the arsenals, acceptance testing at Aberdeen Proving Ground; and, after they were re-established in 1922, administered the Ordnance District offices. The Field Service had charge of all storage depots, maintenance and inspection of Ordnance equipment issued to troops, and all salvage operations.

The Technical Staff was made up of officers and civilians, each a specialist in some field of Ordnance design or manufacture, such as artillery weapons, small arms, tank and automotive equipment, and aircraft ordnance. This group directed Ordnance research in ballistics, the preparation of firing tables, and tests of experimental materiel; kept informed of the trends and progress of ordnance development here and abroad; acted as a clearinghouse for technical information; and built a technical library for OCO. The actual design of Ordnance items was left to the engineers of the Manufacturing Service, but the Technical Staff was authorized to recommend research projects and to approve or reject engineers' proposals for development projects. To more effectively direct the testing of experimental materiel, the Technical Staff was given technical and administrative control over Aberdeen Proving Ground.

General Williams also created an Ordnance Committee to advise the Chief of the Technical Staff and perform certain other important functions. This committee consisted of representatives of the using Arms and Services as well as of the Ordnance Department. Its primary purpose was to enable the Army as a whole to exercise appropriate influence on the design and development of Ordnance materiel. The Ordnance Committee was expected to assemble all the information necessary to establish the military characteristics desired in Ordnance items to be developed; to recommend preliminary design studies of such items; to plan and conduct the necessary service tests of newly-developed items; and to report the results of such tests. The Committee was also to recommend the standardization of Ordnance items. The committee's recommendations were almost always accepted by the General Staff and the Secretary of War. Finally, the Ordnance Committee compiled the Ordnance Department's Book of Standards, which listed, model by model, the items of Ordnance materiel that had been classified and issued to troops.

The organization thus given the Office, Chief of Ordnance, by General Williams remained in effect with only minor changes until July 1941, when the Technical Staff was abolished and its functions given to the Assistant Chief of the Industrial Service for Engineering.

As has been stated, from 1919 to 1940 Aberdeen Proving Ground was under the direction of the Chief of the Technical Staff. When the Research Division of the Proving Ground was organized in 1935, it was automatically under the Technical Staff's control. And, when the Research Division became the Ballistic Research Laboratory in 1938, the relationship with the Technical Staff was continued unchanged.

Apart from the expected cutback of funds at the end of the war in Europe, it was anticipated that the Ordnance Department's peacetime budget would be sufficient to maintain the necessary research and development activities, such as Major Veblen's report had recommended for ballistics. However, by 1921 the postwar business recession had gone so far that the Government as a whole adopted a policy of strict economy. By fiscal year 1923 the Ordnance Department's budget had fallen to $6,100,000, and it declined still further during the next five years, until it failed to attain even its prewar size. In fiscal year 1928, the 1923

figure was regained, and the Ordnance Department's annual appropriation remained fairly constant until 1937, when it was raised to $17,110,000 because of alarming developments in the international situation. The budget for fiscal year 1938 was $24,947,000; for 1939, $112,200,000; and for 1940, about $176,547,000.

The appropriated funds, which averaged only about $11,000,000 annually for the period 1922-1937, had to cover the operations for the entire Ordnance Department, including its six major arsenals and Aberdeen Proving Ground. As a result, the amount that could be allocated for research and development work was scarcely more than $1,000,000 for any one year; even in 1939 and 1940, when rearmament was a major objective of the nation, the sum earmarked for research and development was under $2,000,000.

Lack of funds was paralleled by an insufficiency of personnel and a dearth of specialists. Most of the scientists and mathematicians who had served in the Proof Department of Aberdeen Proving Ground during the war had returned to civilian life.

Under such conditions, ballistic research as well as the other research and development activities of the Ordnance Department would have fared much worse than they did between 1919 and 1940 had it not been for a succession of Chiefs of Ordnance who were keenly aware of the importance of the research and development function to modern military strength.

General Williams, who was Chief of Ordnance from 1918 to 1930, had been in combat in Europe during the war and appreciated fully both the need of line troops for the best weapons and ammunition obtainable and the Ordnance Department's responsibilities for providing such materiel. Working with the greatly reduced budgets of the period between the wars, he nevertheless did much to encourage and support research and development work.

Major General William H. Tschappat, Chief of Ordnance from 1934 to 1938, was well known and highly respected as a ballistician as well as an Ordnance officer. He constantly advocated the application of scientific knowledge to the solution of Ordnance problems, and did much to lay the groundwork for the ballistic research carried out during World War II. From 1922 to 1925 he had been the Commanding Officer of Aberdeen Proving Ground, assisting those engaged in ballistic research to the utmost of his ability.

Major General Charles M. Wesson succeeded General Tschappat in 1938 and served as Chief of Ordnance until 1942. He had been Commanding Officer of Aberdeen Proving Ground from 1925 to 1927 and again from 1934 to 1938, and had served as the Chief of the Technical Staff, OCO, for four years. In all these posts he evidenced a lively interest in research and development, doing much to prepare for the great expansion of these fields that came with World War II.

Because of support by these and other ranking Ordnance officers, ballistic research in the Ordnance Department was not reduced to a level that lack of funds and personnel might have necessitated. Throughout the period between the wars, all of the experimental work and most of the theoretical studies in ballistics were carried out at Aberdeen Proving Ground.

ORGANIZATION FOR BALLISTIC RESEARCH AT ABERDEEN PROVING GROUND, 1919-1935

The World War I organization of the Proof Department for ballistic research remained unchanged until July 1922, although the number of people employed was drastically reduced as soon as the war ended. In July 1922 the Proof Department was divided into the Ordnance (later the Gun) Testing Division and the Automotive Testing Division. The Ordnance Testing Division was subdivided into ten sections, each a separate unit for performing specific proof and test work. This organization lasted without major change until 1935. The subdivisions engaged principally in ballistic work were the Ballistic, Gauge, Instrument, Range Observer, and Camera Observer Sections; in 1925 a War Reserve Section was added for the surveillance of stored ammunition.

In 1925 the Ballistic Section of the Gun Testing Division was enlarged and given an Experimental and a Mathematical Unit. The first of these conducted tests to determine projectile velocities and bomb trajectories, carried on research for improving ballistic instruments, and, in general,

was responsible for all tests and experimental work needed for the study of interior and exterior ballistics. The Mathematical Unit was engaged chiefly in preparing ballistic and firing tables.

Under this organization, ballistic research continued at a surprisingly high level, despite the limitations of funds and personnel.

THE RESEARCH DIVISION, ABERDEEN PROVING GROUND, 1935—1938

The first major reorganization in the period between the wars was made in 1935, when the Ballistic Section was withdrawn from the Gun Testing Division and established as the Research Division, Aberdeen Proving Ground. By this action the groups engaged in ballistic research were for the first time in a position to formulate plans and programs closely meeting the requirements of their special field. Much of the credit for this step forward was due to Colonel H. H. Zornig, who came to the Proving Ground in 1935 to take charge of the Ballistic Section. Although the new Research Division had only about thirty people on its rolls, six sections were set up to cover the several fields of ballistic work.

The Interior Ballistics Section had as its mission mathematical and experimental research for advancing the theory of interior ballistics, study of gun design principles, and investigation of applied technical problems in its field. In addition, it studied the behavior of projectiles and bombs and their component parts on approaching a target. This was classified as effect-of-fire investigations, and marked the beginning of terminal ballistics.

The Exterior Ballistics Section studied the trajectories and flight characteristics of projectiles and bombs. The results of this section's work were used as the basis for computing firing and bombing tables and for designing new projectiles.

The Ballistics Measurements Section developed new principles for and designs of improved ballistic measuring devices and also furnished special measuring services to the other division sections.

•The Ordnance Engineering Section made kinematic analyses of gun mechanisms, measured trunnion reactions, and made mechanical analyses and strain studies of gun mounts.

COL H. H. Zornig, Ballistics Section Head 1935; Director BRL 1941

The Computing Section prepared firing and bombing tables for standard ammunition and bombs, computed fundamental ballistic tables, and prepared ballistic data to be used in improving fire control equipment.

The War Reserve Section (which also had been withdrawn from the Gun Testing Division when the Research Division was formed) continued in its surveillance of stored ammunition.

Each staff member of the new division was required to keep abreast of research and development work under way in the U.S. and abroad that would contribute to the success of work in his special field. In addition, the senior staff members made a continuing analysis of the mission of their division, sought to bring their organization to the highest level of efficiency attainable, and attempted to obtain as many additional specialists as the budget would permit.

It quickly became evident to all staff members that, if the Research Division were to perform its mission satisfactorily, special laboratory facilities

in addition to those already available would be needed. Such facilities would require a new building, however, and lack of funds would not permit construction.

ESTABLISHMENT OF THE BALLISTIC RESEARCH LABORATORY, 1938—1940

In December 1938, to give greater emphasis to its special field, the Research Division of Aberdeen Proving Ground was renamed the Ballistic Research Laboratory, with neither its mission nor its organization changed. Colonel Zornig became the Director of the Laboratory, Captain L. E. Simon was made the Assistant Director, and Lieutenant P. N. Gillon was named the Executive Officer. Mr. R. H. Kent, who had served as an officer in the Ballistics Section, OCO, during World War I and stayed on as a civilian in the Proof Department, Aberdeen Proving Ground, and Dr. L. S. Dederick were made Associate Directors in charge of the Laboratory's scientific work.

Dr. L. S. Dederick, Associate Director of BRL 1938 to 1953

Mr. Robert Kent, Associate Director of BRL 1938 to 1956

This action was really only a change in name, but it had the generally advantageous effect of giving more clear-cut emphasis to the Laboratory's basic mission. Late in 1938 three of the operating sections were subdivided so the different phases of ballistic work could be given the required attention of the specialists. The Interior Ballistics Section was broken down into Mathematical, Mechanics and Heat, Physical Chemistry, and Effect of Fire Units; the Exterior Ballistics Section was given a Mathematical Unit; and the Computing Section was subdivided into Ground Gunfire, Bombing, and Air Gunfire Units.

Until 1940 only minor changes were made in the Laboratory's overall organization, which dated back to the establishment of the Research Division in 1935. An Aerodynamics Unit was added to the

Exterior Ballistics Section, and a Mechanical Section, the forerunner of the Laboratory's present machine shops, was organized in July of that year.

In 1939 the Army Air Corps, grateful for the work that the Laboratory's specialists had done in bomb ballistics, contributed funds for a new building large enough to house the additional laboratory facilities required. This building was completed in 1941.

The part played by Colonel Zornig and his able assistants, Captain Simon, Lieutenant Gillon, Mr. Kent, and Dr. Dederick, in advancing ballistic research at Aberdeen Proving Ground after 1935 can scarcely be overestimated. It was primarily the foresight of Colonel Zornig that was responsible for the creation of the Research Division in 1935 and its evolution into the Ballistic Research Laboratory by 1938. By careful, wise planning he and his associates organized a broad program of research and expansion of facilities that prepared the way for the tremendous progress made in ballistics work during World War II and the postwar period.

GENERAL EXPANSION OF BALLISTIC RESEARCH

The United States Army's experience in World War I had clearly demonstrated the need for improving practically every ordnance weapon — French, British, and American — if the requirements set by the new warfare were to be met. Accordingly, in December 1918, General Peyton C. March, the Chief of Staff, appointed a board of seven officers to plan a comprehensive development program to improve field artillery materiel. Under the presidency of Brigadier General William I. Westervelt, from January to May 1919, this board gathered the data it required by interviewing French, British, and Italian experts, examining Allied and enemy ordnance, conferring with American generals who had commanded combat troops in the war, consulting with the Chiefs of Ordnance, Field Artillery, Coast Artillery, and Chemical Warfare, and inspecting plants in which ordnance items were manufactured.

The Westervelt Board's report stated categorically that every gun, howitzer, projectile, gun mount, and vehicle that the United States Army had in service should be improved, and the report supported this statement by a detailed analysis of the existing inadequacies and defects of the individual items. In order to eliminate these shortcomings, it recommended a broad research program to provide the information on which the design of greatly improved artillery weapons and ammunition could be based.

A good beginning in ballistic research had been made during World War I, when a number of the fundamental problems were recognized and defined. It was realized, however, that much more work was needed, including exploration of new avenues of approach to the many questions yet to be answered. The entire field of interior and exterior ballistics would have to be reworked and expanded.

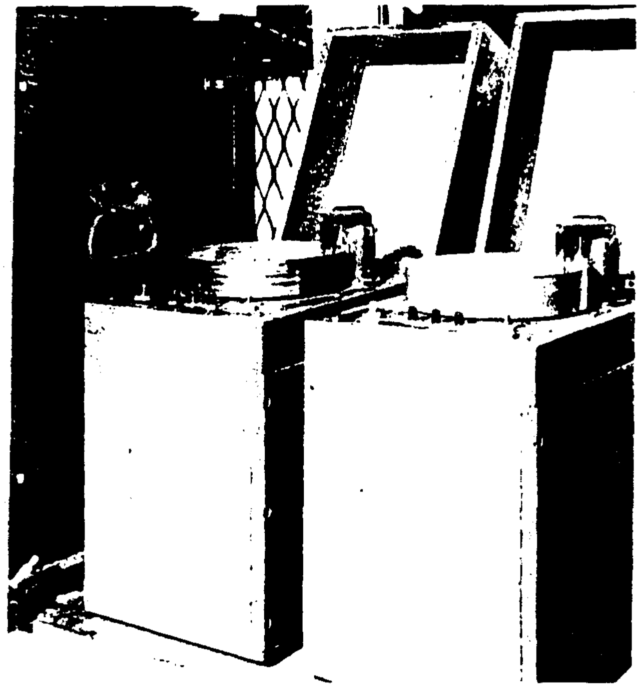
MAJOR PHASES OF THE EXPANSION

Probably the most complex task confronting the Ordnance Department's ballisticians at the end of World War I was the redesign and improvement of ammunition and its components. Artillery experts could specify exactly what the performance characteristics of guns, mounts, and carriages should be, but for projectiles, explosives, propellants, and fuzes they could describe a desired end item in only the most general terms. Basic research in interior and exterior ballistics was needed to improve projectile design, increase the destructive force of high explosives, develop propellants to produce higher muzzle velocities and yet stay within the maximum allowable pressure limits, design improved measuring devices and arrive at sounder mathematical theories and general ballistic procedures. It was also evident that attention must be given to the behavior of projectiles when they reached a target.

Beginning directly after the end of World War I, the Ballistics Branch, OCO, and the Proof Department, Aberdeen Proving Ground, went to work on these problems. Their achievements of the next twenty years are most remarkable — until 1938 there were scarcely more than a dozen specially trained individuals available for the work to be done.

The Utilization of Research Instruments. In addition to standard gauges and other measuring devices from commercial manufacturers, specially-designed instruments were required for many ballistic investigations. Because the phenomena to be recorded frequently involved either very high pressures or extremely high velocities which had to be measured with extreme accuracy, the problem of designing instruments was far from simple. Furthermore, as the scope of ballistic inquiries expanded, constant improvement of the instruments on hand became almost as essential as the design and development of new instruments.

The Aberdeen Chronograph. The Aberdeen chronograph, developed during World War I and put into use in March 1918, was improved throughout the period between the wars. Its principal use was the determination of muzzle velocities and the extent to which a projectile lost velocity over a small section of its trajectory after leaving a gun's muzzle.

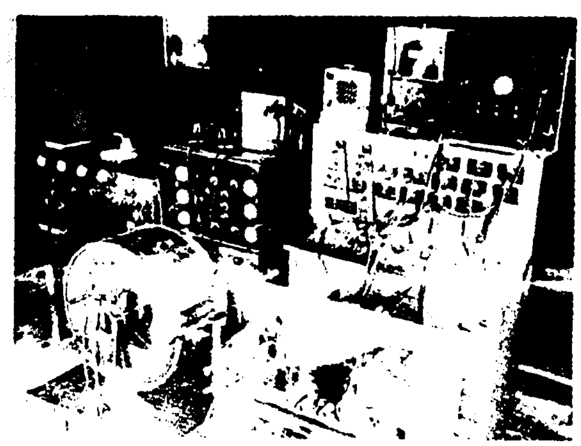


Improved Aberdeen Chronographs Mounted for Field Use

The Camera Obscura. The camera obscura, the principle of which had been known for several centuries, came into use for ballistic purposes when the advent of air warfare in World War I necessitated the preparation of bombing tables. The first system using this device was set up at Aberdeen Proving Ground in 1921. The camera obscura was really a room-size box big enough to contain a plotting board and several men, and fitted with a large lens in either the ceiling or on one side in place of the pinhole of the original device. One such structure was placed at the end of a measured base line on the ground with its lens pointing directly upward, and another was placed at the other end of the line with its lens pointing toward the target area. The vertical box was fitted with a special chronograph, and the two were tied in with the bombing plane by a wireless and telephone communications network. With this system, the exact location of the aircraft at the time a bomb was dropped could be determined from plots of the images in the two cameras, and the time and exact point at which the bomb landed could be observed from a tower. With this information the range and the time of flight data could be computed. As a result, accurate bombing tables were prepared for the Army Air Corps. This system was improved from time to time after it was introduced in 1921, increasing the accuracy of its results.

The Solenoid Chronograph. The solenoid chronograph, considerably more accurate than the Aberdeen chronograph, was developed in the 1920's by E. A. Eckhardt and I. C. Karcher, of the National Bureau of Standards, and R. H. Kent, of Aberdeen Proving Ground. It determined the velocity of a projectile in the first small section of its trajectory after it left the muzzle of a gun. In place of the screens of the Aberdeen chronograph, the solenoid chronograph had two concentric solenoids or coils, placed a given distance apart, through which a magnetized projectile was fired. The electromotive force generated in each coil by the passage of the projectile was transmitted to the galvanometer of an oscillograph camera, which recorded on moving film the galvanometer deflection produced by receipt of the energy from each solenoid, together with time signals obtained from a tuning fork. This was the most accurate and dependable instrument so far devised for determining projectile velocity. It not only made unnecessary the changing of velocity screens after each firing, but also made it possible to determine the velocity of projectiles with extremely sensitive nose fuzes, which neither the Boulengé nor the Aberdeen chronograph could do.

After the first solenoid chronograph had been put into use, its circuits and recording apparatus were measurably improved. A vacuum-tube ampli-



Solenoid Chronograph

fier was added to make possible the use of weakly-magnetized projectiles, and various other minor improvements were made. It has been used successfully to measure the velocity of projectiles of all calibers from 37-mm to 16 inches, fired at all angles of elevation up to 65 degrees. In the late 1920's it was classified as a standard item by both the Army and the Navy.

The Fuze Chronograph. The Aberdeen and solenoid chronographs were useful only for measuring the velocity of a projectile in an abbreviated section of its trajectory near the muzzle of a gun. With the coming of air warfare, it became desirable to determine accurately the time of flight of an antiaircraft shell from the moment it left a gun to the moment it burst. Under the general direction of R. H. Kent, this problem was solved by fitting a photoelectric cell with an amplifier and a relay to the spark points of a slow-speed Aberdeen chronograph. The flash of a gun, picked up by the first photoelectric cell, produced the first spark and the flash of the bursting projectile produced the second; the time elapsing between the two was determined from the record on the drum of the chronograph.

The Photoelectric Chronograph. In the mid-1920's the photoelectric cell again was employed as a means of determining quite simply the velocity of a projectile passing over a measured distance on the ground. Two cells, placed at a given distance from each other on a projectile's course, were activated in turn by the shadow of the projectile passing over them. Their reactions were recorded on a chronographic device, providing an accurate measurement of the projectile's velocity. This instrument was first used in December 1927 and thereafter was employed with either an Aberdeen or a solenoid chronograph to record the velocities of projectiles fired at high angles. Just before World War II it was adapted to determine the velocity of small arms bullets and used frequently thereafter for this purpose.

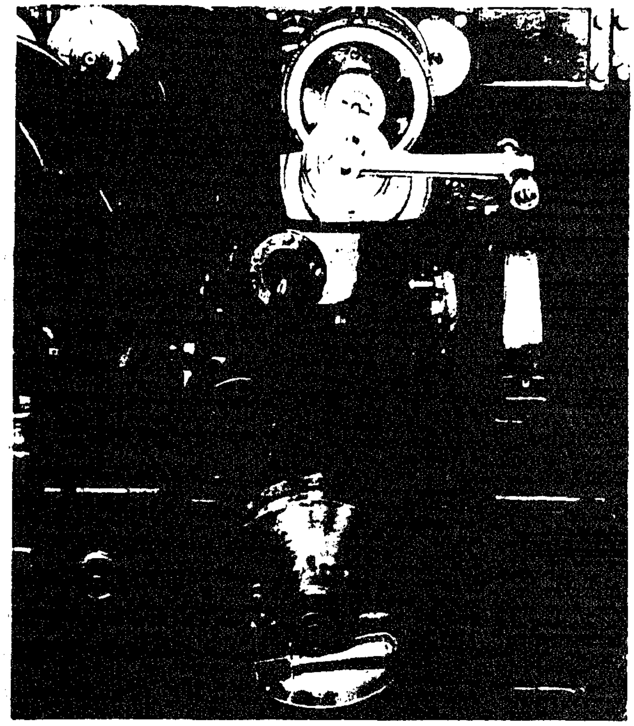
The Piezoelectric Gauge. Until the end of World War I, as has already been indicated, very little of any significance had been done to expand the field of interior ballistics because of the lack of instruments that could measure accurately the short-duration high pressures created in a gun's chamber by the burning of a projectile's propellant. The only practical gauge then available for this purpose was the so-called crusher gauge, developed in the middle of the nineteenth century. It was relatively inaccurate, measured only maximum pressures, and had not been significantly improved since it was invented. In 1917, however, Sir J. J. Thomson of Great Britain made use of the piezoelectric qualities of crystals to measure chamber pressures. In 1919 G. F. Hull began the development of the piezoelectric gauge at Aberdeen Proving Ground, and his work was continued by Eckhardt and Karcher of the National Bureau of Standards and by Kent of Aberdeen. The perfection of the piezoelectric gauge for laboratory use opened the entire field of pressure phenomena to investigation and marked the beginning of a new era for interior ballistics. For the first time, pressure-time curves could be determined from proved data rather than discussed as theoretical. By 1930 the tendency to correlate interior ballistics with investigations of physics and physical chemistry was growing steadily, to the advantage of all three sciences.

The Spark Range. The present spark range at Aberdeen Proving Ground, in which the behavior of projectiles in flight is recorded in detail by high-speed flash photography, was not brought to its advanced state until World War II; nevertheless, during the 1930's the work which led to today's range was begun, and before the Nazis entered Poland some fairly good results had been obtained. Otherwise unobtainable data about the stability of Gerlich-type projectiles and caliber .50 machine gun bullets were provided by the photographs taken in the early range, and enough other data were obtained to substantiate the theory of the motion of projectiles worked out by Kent and H. P. Hitchcock. In general, however, the significance of the work done on the spark range before World War II was in its demonstration of the practicability of this type of precision instrument.

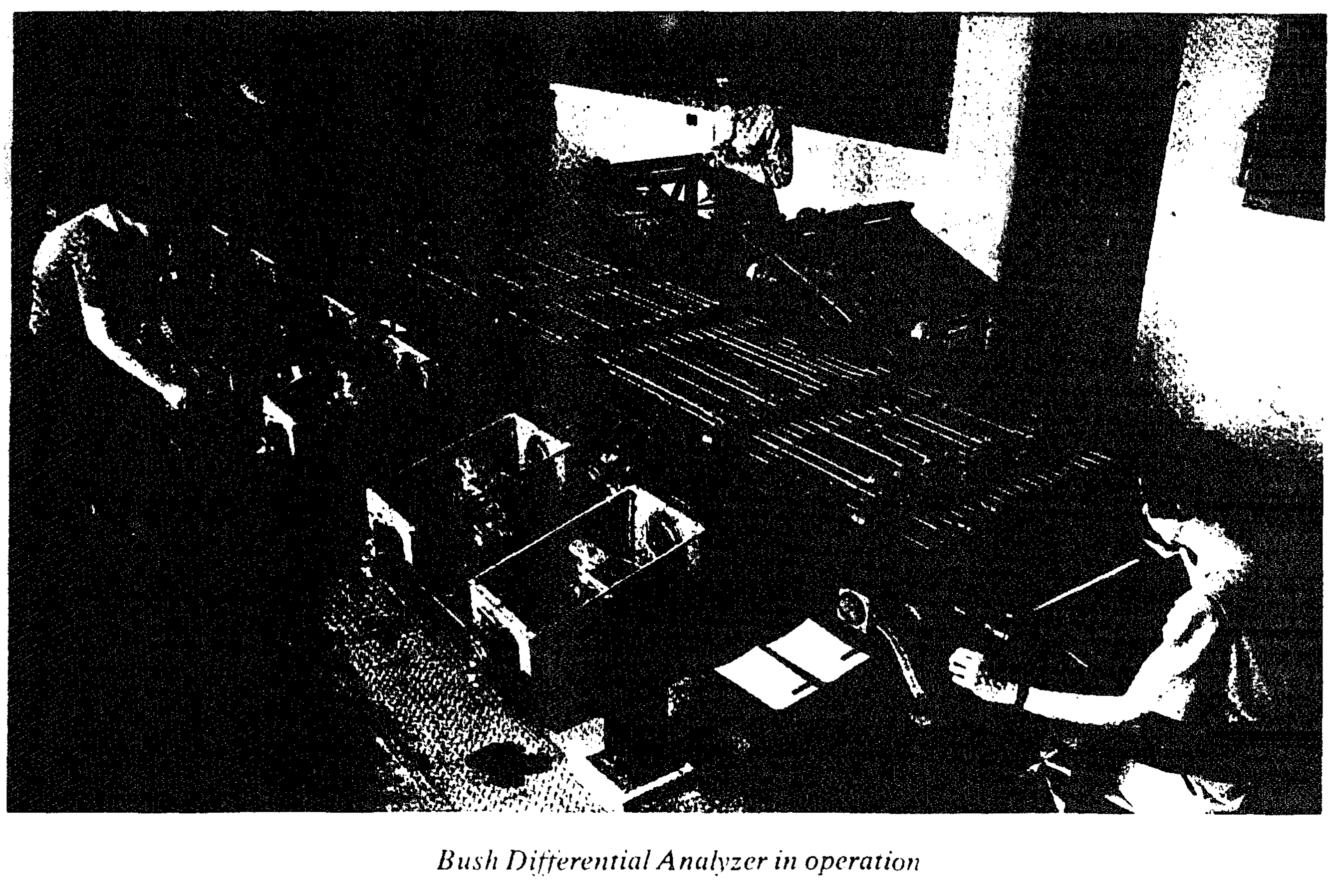
The Blast Meter. The original blast meter at Aberdeen Proving Ground was developed by the National Bureau of Standards and improved in

detail by Kent. Of the piezoelectric type and having a very high natural frequency, its development made possible the study of significant blast phenomena.

The Bush Differential Analyzer. In the early 1930's Dr. Vannevar Bush, of the Massachusetts Institute of Technology, developed a computer for solving differential equations by mechanical integration. In 1934, Dr. Bush suggested that this computer be used to calculate trajectories, but at that time lack of funds prevented the work. A year later Captain Alger also suggested the use of the analyzer for this purpose. His recommendation was approved by Colonel Shinkle, Commanding Officer of Aberdeen Proving Ground, and arrangements were made for Dr. L. S. Dederick, R. H. Kent, and Professor A. A. Bennett to visit Massachusetts Institute of Technology to witness a demonstration. Shortly thereafter arrangements were made for construction of a Bush Differential Analyzer for Aberdeen Proving Ground. The machine was ready for use in 1935. It was used in the preparation of firing



Bush Differential Analyzer; Close-up of Integrator Machine.



Bush Differential Analyzer in operation

tables, and the work required for the tables was reduced enormously. The analyzer's two great advantages were speed and accuracy, and its success marked the beginning of the development of specialized computers for ballistic computations of various kinds.

Other Instruments. A number of other instruments, most of which were procured from commercial manufacturers, were brought into use for ballistic research at Aberdeen. Many of these required no change, but quite a number of others were modified in one way or another to be more adaptable for the work to be done.

Furthermore, a variety of special devices for use in different experiments were developed or adapted by the Aberdeen staff. Among these were various cathode-ray oscillographs for measuring pressure-time curves for small arms ammunition, different types of crusher gauges, a device for measuring the delay of a bomb fuze, and instruments for recording the impact of bombs on land and water. Whatever was required in the form of instrumentation was usually provided in workable form.

Interior Ballistics. The principal objective of research in interior ballistics is increasing the knowledge of such phenomena as the processes of propellant ignition to furnish a sound basis for improving the design of both guns and ammunition. Among the specific objectives to be gained are increased muzzle velocity, uniformity of muzzle velocity, better burning of propellants and elimination of hang-fires, reduction of bore erosion, reduction of muzzle flash and smoke, reduction of gun weight, improved functioning of recoil mechanisms, and better methods of protecting gun mounts against muzzle blast. There were some major advances in interior ballistics during the period from 1919 to 1940, although funding problems caused progress to be less than that desired.

Interior Ballistic Tables. Between 1918 and 1921 Captain A. A. Bennett of the Ballistics Branch, OCO, compiled a complete set of interior ballistic tables, using available data. His tables were based on the integration of three fundamental equations describing, respectively, the energy of the projectile, the motion of the projectile, and the burning rate of the propellant. Bennett's tables were much more accurate than the ones that had been used to that time (which were based on the Le Duc formulas of the 19th century), and are still the basic tables for interior ballistic work on multi-perforated-grain propellants in this country.

The 240-mm Howitzer Experiments. Possibly the most significant work in interior ballistics done at Aberdeen Proving Ground between the wars was the investigation of pressures in the chambers of 240-mm howitzers. These studies began in 1922, as soon as the piezoelectric gauge was available in usable form, and they were concerned with the interrelationships between the propelling charge in a howitzer, the pressure developed by its burning, and the velocity this pressure imparted to a projectile. In order to work out these relationships, full information had to be obtained about such matters as the weight and granulation of powder, size of the powder chamber, weight of the projectile, and length of the barrel.

In the course of this work, the pressure-time and space-time relationships within the cannon's bore during firing were reduced to quantitative form. These data served as a check on pressure and velocity curves that had been determined theoretically. They also made possible a reworking of the formulas used for calculating such curves.

Other information provided by these studies included data on the initial resistance of a projectile, the resistance to the travel of a projectile in the bore, the specific heats of the gases formed by a burning propellant, the burning rate of different powders per surface unit as affected by both pressure and temperature, the co-volume of the molecules of gases, the total energy developed by different powders, and the average exit velocities of powder gases.

By controlling the size of the propelling charge in separate-loading ammunition and making the rear charges of smaller diameter than those before, it was possible to decrease the variation of muzzle velocities. In 1937 Kent, on the basis of the findings from the series of experiments, recommended the adoption of the dual-granulation propelling charges now used in howitzers.

Another important discovery was that variation in muzzle velocity was often associated with sharp increases in pressure waves. This also was used as the basis for making significant improvements in propelling charges.

In similar tests with 3-inch and 75-mm guns, valuable information was obtained about the differential corrections needed to compensate for variations in loading conditions in order to insure uniform muzzle velocities, the kinetic reactions of the powder gases issuing from burning grains of powder, the specific rate at which nitrocellulose burns, and the general thermodynamics of powder gases.

Closed Chamber Experiments. Experiments with propellants conducted in the closed chamber facilities at Aberdeen Proving Ground were closely related to the studies made of the 240-mm howitzer; in effect, their findings supplemented much of what had been learned by the broader program. Valuable data were obtained about the way in which shape of powder grains affects burning rate, the co-volume of gases, and the specific heat of gases.

Exterior Ballistics. In general, research in exterior ballistics between the wars followed the pattern established during World War I. The chief innovations were a general increase in both the scope and the depth of investigations, the mechanization of certain important types of computation, the experimental verification and application of the theory of spinning projectiles, and the establishment of new drag functions for projectiles.

Contributions to Exterior Ballistics Theory. One of the most significant advances in the theory of exterior ballistics made at Aberdeen between the wars was the formulation of the theory of the spin of projectiles by Kent and Hitchcock. Until the postwar period, the movement of a projectile's longitudinal axis relative to its trajectory had not been seriously considered so long as the projectile landed on its nose and its fuze functioned. When the force equation was applied in the problem of accounting for range and accuracy of fire, however, this movement of a projectile's long axis was seen to be significant. In England during World War I, Fowler, Gallop, Locke, and Richmond developed a theory of the motion of a spinning projectile in which its motion was described as being similar to that of a spinning top. When their findings were studied by Kent (who had visited Fowler and learned of his theory and experiments) and Hitchcock, they conducted similar experiments that confirmed Fowler's theory and produced valuable data for use in the design of projectiles. Analysis of tests conducted to prove this theory indicated quite clearly the conditions that would have to be met if a projectile were to remain stable throughout flight (that is, if its longitudinal axis were to be maintained coincident with its trajectory). A numerical index of stability was calculated for each type of projectile and was termed the stability factor. Subsequent experiments verified these computed constants and revealed the relationship between the stability of a projectile and its air resistance (drag), and the crosswind force affecting it. The causes of drift (lateral deflection of a projectile) were analyzed and placed on a computable basis. Although the Magnus force was known to exist, it was not regarded as sufficiently significant at that time to be included in this overall analysis. The general result was the establishment of the spin theory as the basis of exterior ballistics; this theory was used until 1941.

Turning to another aspect of exterior ballistics in 1938, Kent and Hitchcock developed a method for computing the trajectories of bullets fired from antiaircraft guns. The theory for this method was based on Siacci's integrals (inclination, time, space, and altitude functions). Their method proved to be a good approximation even for high angles of elevation for the relatively flat portion of the trajectory employed in antiaircraft fire. The labor of computing trajectories by this method was much less than that required when numerical integration was used; also, the new method enabled the computer to make allowances for variations in air density and variations in the form factor as the result of variations in yaw.

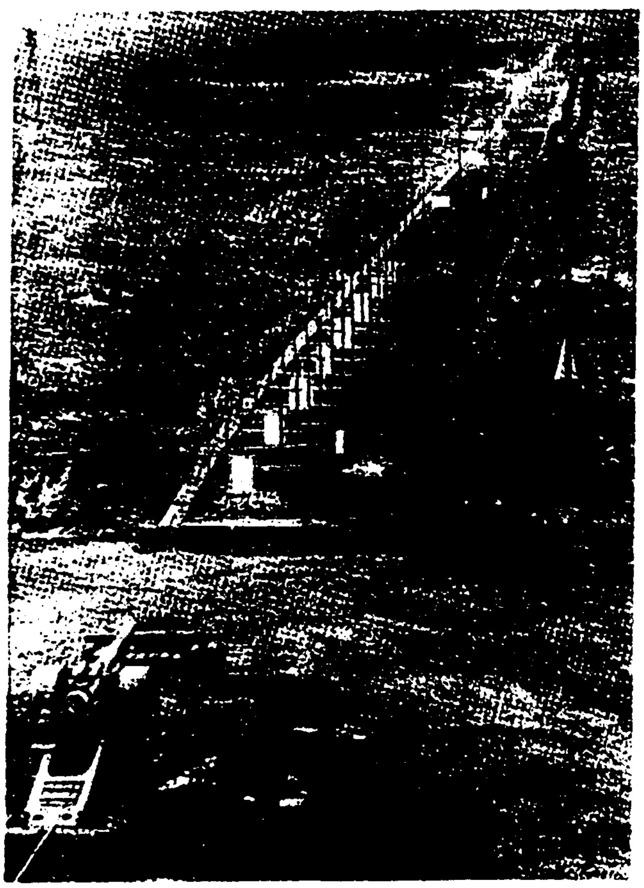
Air Resistance Studies. After World War I, the Ordnance Department, in keeping with its own observations and the Westervelt Board's report,

had a keen interest in redesigning its artillery projectiles. Increased range, greater accuracy, and greater destructive capacity were needed, and they could be obtained only by designing projectiles whose shape, center of gravity, type and location of rotating bands, and metal parts were optimum for the specific job to be done.

One discovery made early in the investigations of projectile design was that a projectile could be lengthened and streamlined to increase the range of a gun without making any changes in the weapon itself. These experiments showed that retardation of a projectile depended primarily on its shape; also, that adequate boattailing reduced the force of the air acting against a projectile by about 40 percent at velocities between 200 and 300 meters per second and by about 20 percent at 330 meters per second.

The firing tests conducted at Aberdeen Proving Ground by Kent and Hitchcock provided for the first time reliable information about the behavior of projectiles in flight. By firing a projectile through yaw cards (a series of cardboard panels placed at set intervals along the projectile's trajectory), it was possible to plot the new trajectory with great accuracy, and determine by measurement of the hole in each card the angle of the projectile's longitudinal axis to its mean trajectory at the moment it went through that card. These tests showed that the motion of a projectile about its center of gravity, as evidenced by the movement of its longitudinal axis in relation to its trajectory (yaw), was similar to that of a spinning top; thus the base of the projectile, for example, tended to follow a spiral around the mean trajectory.

Holes made by a 3" shell in yaw cards.



Field setup showing dense distribution of yaw cards for stability firing.

From these tests two additional types of information were obtained. Much was learned about the aerodynamic forces that operate on projectiles in flight. Secondly, Kent and Hitchcock were able to use the test data in calculating stability factors for different generalized types of projectiles; these factors proved to be very useful in subsequent projectile design.

Throughout this work it was assumed (as it has always been assumed) that only two forces act on a projectile in flight — gravity and air resistance. When a shell yaws, the air resistance is directed at an angle with the direction of motion; the component that opposes the direction of motion is defined as drag. The drag divided by the product of the air density, the square of the caliber, and velocity is given as the drag function, denoted by the symbol G, so termed from the French Commission under whose direction it was first calculated for the Gavré projectile. Kent and

Hitchcock found that a projectile with a 6-degree boattail and a long conical head had an entirely different drag function — one that could not be expressed as a multiple of the Gavré drag function. They proceeded to calculate drag functions for the projectiles of other configurations and assigned to each of them the symbol G with an appropriate subscript. Using G_1 to represent the Gavré resistance function, they listed the ones they had calculated as G_2, G_3, G_4, etc. The Gavré projectile (the prewar type) was identified as Type 1 and the projectiles to which their drag functions had been calculated were identified as Type 2, Type 3, Type 4. etc.

Compilation of Exterior Ballistic Tables. The need for exterior ballistic tables had been greatly reduced by Aberdeen's acquisition of the Bush differential analyzer. As originally planned, the ballistic tables were to be used for compiling firing tables for specific gun-ammunition combinations; however, the Bush analyzer made possible the compilation of firing tables directly and much more rapidly than could be done by any older method.

Despite this, the three volumes of tables so produced are still in use. They are excellent for obtaining approximate answers to the questions that always arise during the design of new projectiles.

Compilation of Firing and Bombing Tables. Throughout the period between the wars — and especially after 1935 — firing tables were produced in great numbers for both artillery weapons and small arms. Such tables were prepared for each new gun and projectile, and many of those already in use were revised in light of new ballistic knowledge and procedures. This period saw the first serious attention given to firing tables for small arms, which is explained by the extensive use made of machine guns during World War I. As the war had progressed, the range of machine guns had been measurably increased, but the firing tables available for their ammunition were unreliable for ranges above 1,000 yards. To remedy this situation, in 1921 a special small arms firing range was established at Aberdeen Proving Ground to provide the data needed for the preparation of accurate and reliable firing tables for such weapons. This was later supplemented by the development of a rudimentary spark range, which provided additional data by the use of high-speed flash photography. In this way the desired firing tables were produced and facilities were provided for investigation of other aspects of both interior and exterior ballistics of small arms. The differential analyzer was used regularly after 1935 in preparing firing tables for small arms and artillery.

Bombing tables, however, were not computed mechanically. Before 1940, only one bombing table, based on the Gavré drag function, was used. The data required for each bomb were obtained by the camera obscura group, and then analyzed. Very accurate tables were prepared for use by the Army Air Corps, but the amount of work involved was great.

Recoil Studies. The studies of the 240-mm howitzer yielded a great deal of information about the recoil of cannon. To supplement this, in the early 1930's Kent carried out a number of experiments to obtain specific information about the dynamics of automatic weapons, in the course of which he developed an improved method for measuring recoil forces. This method was in general use at BRL by 1940 but nowhere else, even as late as 1975.

Meanwhile, Kent had evolved a theory of recoil action which served as the basis for the design of a recoil mechanism for automatic guns. This mechanism is still used and is known as the *soft recoil system.*

Effect-of-Fire Experiments. Although large-scale support of weapons effectiveness studies and aircraft and armored vehicle vulnerability programs was definitely post-1945, quite a number of investigations with similar objectives were conducted at Aberdeen Proving Ground during the period between the wars.

A long series of tests was run to determine the fragmentation characteristics of different bombs and shell, especially the 75-mm HE shell. These tests included the pit, panel and silhouette tests, to determine the number and spatial distribution of fragments, and the number of fragments capable

of wounding an individual. The criterion for this capability was the ability of a fragment to perforate a 1-inch pine board.

Although valuable, these tests had a number of shortcomings because the variables were not determined in engineering and scientific units that could be adapted to new sets of conditions. Mr. Kent made suggestions on how to improve fragmentation investigations. In 1934 he suggested to OCO that in order to measure and evaluate capabilities of fragments to damage a target, the ballistician must know the number of fragments produced by the detonating projectile, the velocities of the fragments as dependent on the size and part of the shell from which they are emitted, and their ballistic coefficients, by means of which it would be possible to calculate velocity loss as a function of distance from the point of detonation. This information, together with data obtained on the penetration capabilities of fragments of known mass and velocity, would provide a firm basis for the calculation of the effectiveness of fragmenting projectiles against various types of targets. Kent's suggestions were made at a time when little was known about fragmentation phenomena, but they have since been adopted in their entirety by all personnel working in this field of ballistics.

During the middle 1930's and later, Kent had moderate success in measuring fragment velocities by using the Aberdeen Chronograph; he also fired single bomb fragments from a gun to determine their ballistic coefficient. However, several years were to elapse before measurements and calculations of these types could be made with sufficient accuracy.

As early as 1925 interest in the effectiveness of antiaircraft shell became active, the first tests being those of 3-inch antiaircraft shell. The fragmentation characteristics of these shell, including relatively complete information about the velocity and pattern of the fragments they emitted, were determined by firing them against aircraft until sufficient damage had been done to necessitate major repairs. The damage was carefully studied and analyzed in terms of the shots fired. Other tests involved the detonation of bombs of different sizes and the firing of caliber .30 and caliber .50 machine gun bullets against aircraft with running engines to determine the relative effectiveness of such weapons against aircraft targets. Charts were made to show the distribution of hits by bomb fragments and bursts of machine gun fire, and both moving and still pictures were taken of the damage done. In other tests, 15-pound bombs were suspended beneath the wings of an aircraft and detonated to determine the extent of the damage they would do to both wings and fuselage. Again, bombs similarly suspended were fired on by caliber .50 AP bullets to find whether they could be detonated by enemy small arms fire.

On the basis of firing tests for evaluating a number of different antiaircraft guns, it was recommended that the 90-mm weapon be adopted because of its superior over-all effectiveness.

The effectiveness of antitank weapons also was investigated. In 1925-1928, caliber .30 and caliber .50 AP bullets, 37-mm AP shot, and 57-mm AP shot were fired against obsolete Renault tanks; the results showed that this tank was vulnerable only to the 57-mm shot. Many other tests were conducted to determine the armor-piercing capabilities of different bullets and shot.

As a result of all this work, when more comprehensive programs to determine weapon effectiveness and the vulnerability of aircraft and armored vehicles were instituted during and after World War II, considerable information was already available for use.

Surveillance of War Reserve Ammunition. Much detailed work is required to maintain continuous records of the service usefulness of large stocks of ammunition in storage as war reserves. Surveillance reports from the field must be analyzed and the results compared with the records of earlier tests, and programs for the inspection and firing of representative samples must be planned. Each lot of ammunition and ammunition components must be graded and a decision made as to whether it should be disposed of or retained. This work was done before 1935 by the Surveillance Section of the Gun Testing Division, Aberdeen Proving Ground; in 1935 it was transferred to the War Reserve Surveillance Section of the Research Division.

The greatest contribution made by Aberdeen workers to this field in the period between the wars was the application of statistical methods to the surveillance problem, accomplished under Captain

Simon in the late 1930's. Procedures were developed for selecting lots to be tested, determining the sampling, inspection, and test actions to be taken, evaluating the results, and grading the lots in terms of these results. The complete system, based on good engineering and industrial statistical methods, was in operation by 1938 and has been considerably expanded since that date.

Research on Rockets. The development of the rocket as a major weapon of modern warfare did not take place until after World War II had begun, and, consequently, little was done between the wars in the field of ballistic research for rockets. However, in the 1930's Lieutenant Leslie A. Skinner, on his own initiative and with makeshift equipment, conducted a number of tests at Aberdeen Proving Ground to obtain information that would be useful in rocket development. While his work was inconclusive, his findings indicated broadly what should be investigated once the development of rockets was seriously undertaken.

The Technical Library. When the Ordnance School was moved to Aberdeen Proving Ground in 1918, it brought with it a technical library consisting of some 3,000 volumes collected during the war. Shortly thereafter, the mathematical library of Professor Bocher of Harvard University was purchased and added to the collection; it contained many French and German books and a large number of useful mathematical papers.

In 1921 the Bocher collection was loaned to the Technical Staff of the Office, Chief of Ordnance, when the Ordnance School was transferred to Watertown Arsenal. Largely through the efforts of Colonel Tschappat, Commanding Officer of Aberdeen Proving Ground from 1922 to 1925, most of this collection was returned to Aberdeen and a program was instituted for expanding the Proof Department's library facilities and obtaining additional scientific and technical works and a large number of foreign scientific journals.

From these beginnings the Technical Library continued to grow throughout the period between the wars. By 1940 it contained an excellent collection of technical, scientific, and mathematical works, and was especially rich in the materials most needed for ballistic research.

Machine Shop, such as sweeping, taking out the trash, and oiling certain machines. Safety requirements were strictly adhered to, and Shawn was issued gloves, safety glasses, ear plugs, and safety shoes.

"Rod Ewing, principal of John Archer, recently visited the students at their work sites and said he was impressed with the work assignments and the growth of the students since they began their work at the Laboratory. The [BRL] has been cited for its commitment to the Equal Employment Opportunity program by being named for the past two consecutive years as the winner of the APG Organizational Award for support of disability awareness programs. The Laboratory was also the recipient of the Public Employer of the Year Award for 1990 by the Harford County Committee on Employment of People with Disabilities. Most recently, the Laboratory was recognized as the Medium-size Public Employer of the Year by the Maryland Governor's Committee on Employment of People with Disabilities."[25]

The BRL was even more creative when they "extended their partnership with the John Archer School by establishing a maintenance service contract with the school in September 1991. Twice a week, 4–5 students and a supervisor arrive at the Laboratory to create and maintain various horticultural projects. Indoors, they are responsible for maintenance of live potted plants/flower gardens, artificial plants and arrangements, and relocation of indoor flower beds, etc. The students create many seasonal decorative projects, i.e., for Memorial Day they made arrangements that included small American flags. The program was extended through the summer months so they could maintain the outdoor projects that were started when the contract was awarded.

"The BRL specially leased and outfitted a modern trailer (with heat, air conditioning, rest room, hot/cold water, and refrigerator) for the students to use as a work area/classroom. This trailer provides a comfortable environment for the students to do all the work needed to transplant plants, make seasonal arrangements, grow seedlings, etc. Their tools and equipment are stored in the trailer. These special provisions have enabled the students to get a lot accomplished in a short amount of time, with noticeable results. The students show pride in their work. Many complimentary comments have been received from within the BRL and outside the BRL on this special partnership.

"The expansion of this partnership has been very rewarding, for the BRL as well as the students. For the students, it is a learning opportunity, a chance to practice new skills, to demonstrate teamwork, and a chance to earn a paycheck. For the BRL, it is an opportunity to reach out to the installation, to the community, and to these special students. Through the students' efforts, a more attractive environment has been created. All those entering the grounds of the Laboratory can see the work that has been accomplished through the efforts of the John Archer students. The students were treated at the end of the school year with a tour of the [APG] Ordnance Museum. The John Archer School presented Susan Johnson[26] a Certificate of Appreciation in June 1992 for her support of the program."[27]

The Harford County Chamber of Commerce gave its Partnership Award for Administrative Services given to Harford County Schools during 1991–1992 to the BRL, and Dr. John T. Frasier, Director of the BRL, was cited for his "sincere interest and participation in the Aberdeen High School Partnership Program, 1991–1992."[27]

Awards to the People of the BRL. Over the years, the people of the BRL have received numerous prestigious individual awards including the Army's Exceptional Civilian Service Award, the Army's Meritorious Civilian Service Award, and the Army's R&D Achievement Award. Of particular importance have been the awards that have been bestowed

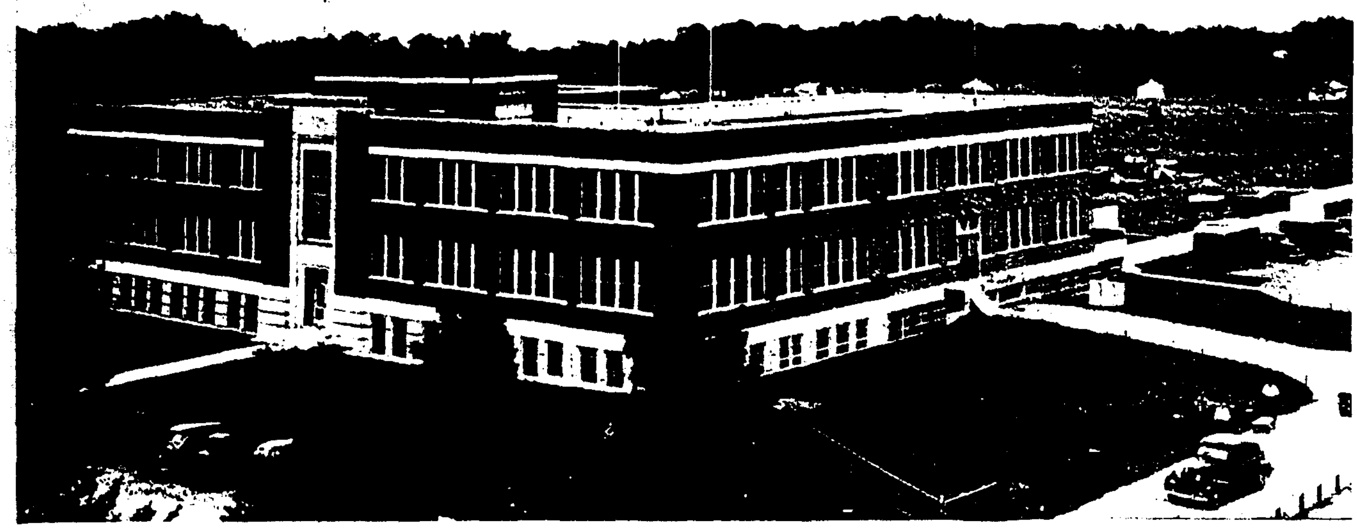
ADMINISTRATIVE CHANGES TO MEET WARTIME NEEDS

Colonel Zornig's plans were fully realized in the years from 1940 to 1945, when the pressing demands of global warfare placed a high premium on all that was known or could be learned about ballistics. The hours he had spent with his aides in drafting organization, policy, and program for a ballistic research center for the Army were more than repaid by the relative ease with which the wartime expansion of his Laboratory proceeded. Had the foundations not been laid in peacetime (and, it must be remembered, when many people in this country were either indifferent or opposed to U.S. involvement in European problems), the Ballistic Research Laboratory would have been faced with complex problems of basic planning at a time when its services were greatly needed to solve urgent problems of applied ballistics.

Fully organized by 1940, the Ballistic Research Laboratory expanded in a rapid but orderly manner. From 65 people in 1940, when America's first draftees were mustered into military service, its staff increased each year, so that by V-E Day it numbered 729. From an appropriation of $120,000 in 1940, the annual budget increased more than tenfold during the war years, reaching $1,600,000 for fiscal year 1945. New equipment and new facilities were added to expedite the work, and the country's scientists were carefully screened in order to obtain men whose knowledge and experience would supplement that of the specialists of the peacetime staff.

Recognition of the high caliber of this organization and the value of its contributions was not delayed until the fighting overseas had ended. Officials who had studied the Laboratory's reports and visited its facilities at Aberdeen Proving Ground were impressed by what they found. Addressing the United States Senate in 1943, the Honorable James M. Mead of New York urged that *every member of the Senate make the journey to Aberdeen to see the great contribution that the men of the Army Ordnance Department and of science are making to our effort.* Extending his remarks in the *Congressional Record,* the Senator stressed the value to the Government of a scientific laboratory which employed techniques not to be found in civilian laboratories:

> *Even if suitable scientific laboratories were prepared to carry on the type of work needed in the design and development of the weapons of war, the time factor alone renders it imperative that the Military Establishment have under its direct control a competent scientific organization to deal*



BRL building before addition of Computing Annex.

with these matters. New offensive weapons to surprise the enemy must be continually developed and weapons or armaments to neutralize the new enemy weapons also [must be developed]. The more rapidly these developments are brought about the more effective they will be on the field of battle. To obtain the utmost rapidity, an organization under the direct control of the Army is essential. Such an organization is to be found at the Army's Aberdeen Proving Ground. . . .

Machine shop — checking a missile model for dimensional tolerance.

Preparing nitric acid, from which nitrocellulose is to be made for use by the Interior Ballistics Laboratory.

Changes in the Organization. The Ballistic Research Laboratory moved into what is now its main building in 1941, where the facilities were adequate for the work to be done. Office space was sufficient, and the laboratories were supplied with gas, water, compressed air, alternating current of any frequency required, direct current, and a great variety of scientific instruments and equipment, including special devices that measured time in microseconds and length in microns. At the same time, the staff acquired good facilities for what had become an excellent technical and scientific laboratory, and also a well-equipped machine shop.

Shortly after the move was completed, a minor reorganization of the Laboratory was carried through — the first of a series of organizational changes that had to be made as functions and staff were expanded to meet the war's demands. In general, the successive changes followed the trend of establishing individual units to carry on specialized research. The reorganization of 1941 produced the following pattern of operating sections:

Interior Ballistics Section

- Theory Unit
- Physical Chemistry Unit
- Mechanics and Heat Unit
- Effect of Fire Unit
- Special Problems Unit

Exterior Ballistics Section

- Mathematics Unit
- Aerodynamics Unit

Ballistic Measurements Section

Ordnance Engineering Section

Computing Section

- Ground Gunfire Unit
- Bombing Unit
- Aircraft Gunfire Unit
- Differential Analyzer Unit

Surveillance Section

In mid-1942 all sections were raised to branch status; the Special Problems Unit of the old Interior Ballistics Section was made a Branch, and a Rocket Branch was set up to concentrate on work in this new field of ordnance. At the same time, the old units became sections and each of the operating branches was given new responsibilities. Also, the Effect of Fire Section of the Interior Ballistics Branch was renamed the Terminal Ballistics Section, thus giving notice of the expansion of the science of ballistics that was in process. So rapid was the growth of this new field that within less than a year the Terminal Ballistics Section was withdrawn from the Interior Ballistics Branch and elevated to branch status.

The Defining of Responsibilities. In August 1943, Ordnance Department Order 80 redefined the entire field of Ordnance research and development, designated the major Ordnance agencies responsible for specific research and development work, and assigned to each agency the special fields of interest to be given primary and secondary attention. Replacing ODO 48 of June 1934, which had been far more general in defining the same problem but had not assigned specific field of interest to any field installation, this order named the Ballistic Research Laboratory as the principal research organization of the Army's Ordnance Department.

The Ballistic Research Laboratory's research and development responsibilities were generally defined as (1) to conduct such basic and technical research as it related directly to the fundamental principles of ordnance and, (2) to develop through experiment special materiel of radically new design and to manufacture such special items (for the most part, instruments and devices for use in research and experimental work) as might be called for. Specifically, the primary responsibilities were listed as follows:

Basic Research

- Determination, evaluation and formulation of fundamental principles underlying design and operation of ordnance materiel

Technical Research

- Application of results of basic research to generic problems and to new types
- Observation, measurement and mathematical treatment of ballistic and other ordnance phenomena
- Compilation of tabular data
- Application of statistical theory to Surveillance

This detailed statement of major responsibilities represented to a great extent the policies and programs that the Ballistic Research Laboratory had established in the preceding decade.

The status given the Ballistic Research Laboratory by this, the first detailed directive to all the research and development agencies of the Ordnance Department, did not affect the control of the Laboratory which, since the Technical Staff was replaced by the Technical Division in June 1942, had been vested in the Technical Division, OCO. (It should be noted that, from July 1941 to June 1942, supervision of the Ballistic Research Laboratory had been the responsibility of the Assistant Chief for Research & Development of the Industrial Service, OCO.) With the establishment of the Technical Division, the direction of all research and development was centralized for the first time in an office at divisional level.

Within the Technical Division, the Ballistics Section of the Service Branch (later renamed the Research & Materials Branch) was assigned the supervision of the Ballistic Research Laboratory. Its control, which was exercised directly and not through Aberdeen Proving Ground, was normally of the broader aspects of the Laboratory's activities; specific problems of programs and projects were handled by the Laboratory itself. Regardless of their origin, requests for work to be done by the Laboratory went to the Ballistics Section for approval, assignment, and allocation of priority. The Ballistics Section also coordinated the work of the Laboratory with that of other Ordnance facilities and agencies outside the Ordnance Department.

From 1947 through 1956, there was practically no change in the way the Ballistic Research Laboratory was administered by the Office, Chief of Ordnance. The change in the Technical Division's title to Research & Development Service in June 1944 and, again, to Ordnance Research & Development Division in the fall of 1946, in no way affected this relationship. The Ballistics Branch continued to be responsible for the direction of the Laboratory's work.

The Ordnance Research & Development Center, APG. When the wartime work at Aberdeen Proving Ground continued to expand, it was decided that the Commanding Officer of the Proving Ground could more effectively administer the test and research facilities under his command if they were grouped under one organization. Consequently, in August 1944 the Proof Service and the Ballistic Research Laboratory were combined and named the Ordnance Research & Development Center. This grouping was solely for the purposes of local administration and in no way affected the relations of the Center's components with the Office, Chief of Ordnance. Acceptance tests of new weapons and ammunition continued to be conducted under the direction of the Industrial Division, and ballistic research and testing of new materiel remained under the direction of the Technical Division, OCO. After it became part of the Ordnance Research & Development Center, the Ballistic Research Laboratory continued to receive its directives and funds from the Technical Division, OCO, and these were not subject to change by any lower echelon in the chain of command.

LEADERSHIP

The Ballistic Research Laboratory's success in performing its wartime mission was attributed to the quality of its leadership, the competence of its staff, and the extent to which good teamwork characterized the attack on all problems, large and small. In addition, the large roster of expert consultants available when needed represented all fields of scientific and technical knowledge related to ballistic research; the experts possessed a collection of frequently-needed information far greater than that which the staff of any laboratory could hope to have immediately at hand.

The Executive Staff. In 1941 Lieutenant Colonel Simon, who had been Assistant Director since 1938, succeeded Colonel Zornig as Director of the Ballistic Research Laboratory and held that position throughout the rest of the war and for several years thereafter. Through Colonel Simon's outstanding work in the application of statistical procedures to the quality control of War Reserve ammunition, conducted before 1941, he earned a high reputation and acquired good insight into the details and principles of administering ballistic research. As Director, he made a continuing study of the trajectories of bullets fired from the sides of aircraft in flight, in order that he might not lose touch with either experimental techniques or the special needs of laboratory personnel. In early 1944 Colonel Simon went to the European Theater of Operations (ETO) to survey the stocks of artillery ammunition being accumulated for the invasion of the Continent and to assist the Chief Ordnance Officer, ETO, in other respects. When our troops

LTCOL L. E. Simon, Director of BRL 1941 to 1949

entered Germany at the end of 1944, he accompanied them to question the staffs of captured German scientific establishments and examine their laboratory equipment, in an effort to find how the Germans had bridged the gap between research and the production of new weapons. His detailed report on this general subject was subsequently used as the basis for his *German Research in World War II*, which was an illuminating account of research organization under the Nazis and the wartime achievements of the German ballisticians.

Major Gillon, who had been the Executive Officer of the Laboratory since 1938, was made the Assistant Director when Colonel Simon succeeded Colonel Zornig. Kent and Dederick continued their work as Associate Directors and, in addition, served as the Chiefs of the Interior Ballistics Section and the Exterior Ballistics Section, respectively. During Colonel Simon's absence overseas, Kent was relieved of his duties as Chief of the Interior Ballistics Section to serve as Acting Director of the Laboratory.

All three of Colonel Simon's principal aides continued to participate actively in ballistic research, despite the heavy pressure of their administrative duties. Coupled with the administrative ability of the four men, this pressure gave them the opportunity to develop the teamwork that characterized the Laboratory's wartime operations.

Recruiting of Scientists. Dr. Oswald Veblen, then of the Institute for Advanced Study at Princeton, came back to the Laboratory as a consultant in April 1942, and proved to be one of the most successful recruiters of scientific talent. Through his pioneer work in ballistics at Aberdeen during the first war, and his brilliant career as a theoretical mathematician between the wars, he knew better than most what qualifications were needed and who among his colleagues could best provide them. Through his efforts, the Laboratory obtained the very valuable services of E. P. Hubble of the Mount Wilson Observatory, T. H. Johnson of the Bartol Research Center, H. B. Lemon of the University of Chicago, Joseph E. Mayer of Columbia University, E. J. McShane of the University of Virginia, and D. L. Webster of Leland Stanford University. Other eminent scientists who became members of the Laboratory's staff during the war, either as civilians or officers, included A. A. Bennett of Brown University (who had been in the Ballistics Branch, OCO, in World War I), Gregory Breit of the University of Wisconsin, T. D. Carr of Duke University, Subrahmanyan Chandrasekhar of the Yerkes Observatory, Nephi A. Christenson of the Colorado State College, J. C. Clark of the Michigan State College, A. L. Gerard DeBey of Purdue University, Lewis A. Delasso of Princeton University, R. B. Dow of the Penn-

First meeting of the Scientific Advisory Committee, Ballistic Research Laboratory, September 1940. Front row, from left: Mr. Kent, Prof. Urey, Prof. Rabi, Dr. Dryden, Dr. Lewis, COL Zornig, Dr. Hull, Prof. von Karman, Prof. von Neumann, Prof. Russell, Dr. Dederick. Second row, from left: LT Gillon, Mr. Lane, Mr. Reno, Mr. Hitchcock, Dr. Charters, CAPT Simon, Dr. Hodge, Mr. Beeman, Mr. Tolch, Mr. Gay, LT Steele. Third row, from left: Mr. Moerman, Mr. Dickinson, Mr. Carr, Mr. McNeilly, Mr. Shanks, Mr. Leeder.

sylvania State College, Joseph A. Frazer of the University of Buffalo, Robert T. Knapp of the California Institute of Technology, Charles B. Morrey, Jr. of the University of California, Theodore B. Sterne of Harvard University, and John B. Vinti of the Worcester Polytechnic Institute.

The work of the resident staff was supplemented by that of the Scientific Advisory Committee, which met at the Ballistic Research Laboratory three or four times a year throughout the war, but whose members were generally available for individual consultation. In addition to advising on scientific and technical programs and problems and assisting in recruiting scientific personnel, the Committee acted as a bridge between the Laboratory and the scientific world. The members who served longest and who were most active were H. L. Dryden of the National Bureau of Standards, A. W. Hull of the General Electric Company, T. von Karman of the California Institute of Technology, Bernard Lewis of the United States Bureau of Mines, J. von Neumann of the Institute for Advanced Study, I. I. Rabi of Columbia University, H. N. Russell of Princeton University and H. C. Urey of Columbia University.

Meeting either as a group or as individual consultants, the members of the Scientific Advisory Committee reviewed the work of the Laboratory's resident staff, assisted in planning the research programs, and kept the Laboratory informed of the new work being done in their fields. By their careful consideration and keen discussion of ballistic problems they gave valuable insight into the causes of problems frequently encountered, and so helped to accelerate their solution.

PROMOTION OF A SCIENTIFIC ATMOSPHERE

Colonel Simon was keenly aware that, even in wartime, a research establishment must have more than personnel, facilities, and funds if it is to be successful in extending the frontiers of knowledge. As he explained, *An excellent organization, powerful backing, and magnificent plant and equipment are no assurance of successful research unless real research leaders are present, and* [*are*] *given the latitude to pursue their work in their own way.* Enough has been said to show that the Ballistic Research Laboratory had the organization, the people, the backing, the facilities, and also the leaders. Colonel Simon and his principal aides were able to convince the authorities in the Office, Chief of Ordnance, that the Laboratory had to give its scientists the freedom to pursue their work in their own way, provided it was directed toward the solution of the wartime problems assigned to the Laboratory by the Ballistics Branch, OCO. It is noteworthy that, even when the pressures of the war's demands were great, no areas of research were assigned priority by any other agencies or offices outside the Laboratory.

Within the limits imposed by security regulations, the staff members were encouraged to present papers and publish articles describing their work at the Ballistic Research Laboratory, and funds were provided for attendance at scientific meetings. Even so, most of the reports of the work done were necessarily issued as classified technical notes, memoranda reports, and scientific and technical reports of the Laboratory, for official use only. Nevertheless, by the time the war was fully under way the circle of scientists with a recognized *need to know* had grown so large that even classified publications did much to enhance the professional reputation of a report's author.

* * *

By such means the Ballistic Research Laboratory not only met most commendably the demands made of it during the war, but also, in doing so, contributed much to the growth of ballistics and laid firm foundations for continued expansion after V-J Day.

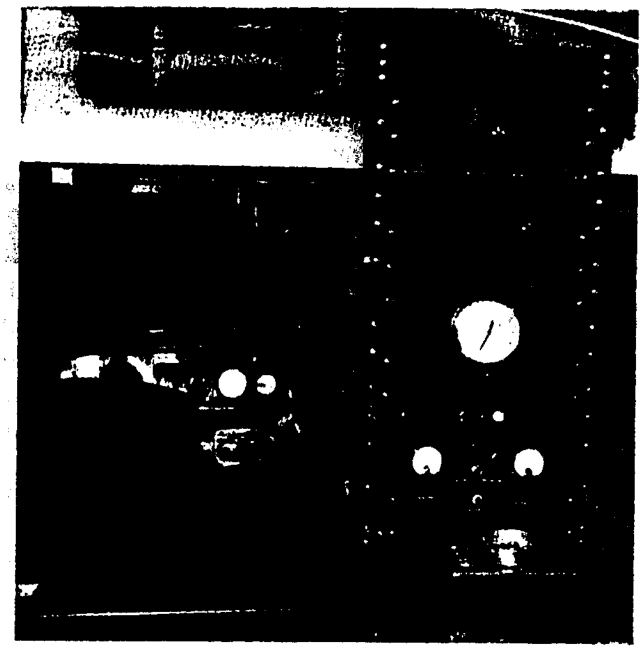
Because the Ballistic Research Laboratory's wartime accomplishments in all fields of ballistics depended so much on the continued improvement of precision instruments, a general account of the development of instruments is given before attention is turned to the work done in the fields themselves.

INSTRUMENTS FOR BALLISTIC MEASUREMENTS

The great majority of new instruments and improvements in those already at hand at BRL were designed and made at the Laboratory itself. This was in strong contrast to the practice of the German ballistic establishments during World War II, and was distinctly to the advantage of the American organization. The instruments used by the Ballistic Institute of the Technical Academy of the Luftwaffe, for example, were for the most part provided by the great German instrument firms, who were inclined to produce only devices for which a considerable market could be anticipated; as a result, many of them were imperfectly suited to the work to be done. At BRL, on the other hand, whatever was needed for the solution of a particular problem was improvised and, if it were found to have a general application, the improvisation was refined and produced for wider use.

Chronographs. Throughout the war the development of chronographs concentrated on obtaining instruments of greater accuracy to determine the velocity of the new types of projectile being brought into use. In addition, full attention was given to making the new instruments as mobile, rugged, and simple in operation as possible, so that they could be used for calibrating guns in the field as well as in research and test work at Aberdeen Proving Ground.

One of the first of the wartime instruments to be put into use was the T2 field chronograph, which closely resembled the Aberdeen Chronograph but used solenoid coils and required magnetizing projectiles whose times of flight it measured. It differed from the earlier model chiefly in that it was considerably more mobile, less subject to malfunctioning as a result of handling in operation, and somewhat more accurate. However, in its original form it could not be used for measuring the time of flight of many small arms bullets, which contained insufficient metal and could not be magnetized. To overcome this difficulty, a plan was made for placing two or more grounded conductors, connected to the chronograph proper, at measured intervals beneath a bullet's line of flight. Inasmuch as any projectile acquires an electrostatic charge in flight, which will induce a charge in a grounded conductor near which it passes, such an arrangement could record the time interval required for a bullet to pass over the distance between the conductors. The operation of this modified system was somewhat complicated, however, by the fact that the electromagnetic charge induced in a projectile was not constant throughout the projectile's flight, so that the measurements made were not always as accurate as those obtained with a solenoid chronograph; however, they were sufficiently reliable for most practical purposes, if not for research.



T2 Field Chronograph mounted in truck for field use

The T3 field chronograph, also called the spin chronograph, was a by-product of the development of the VT fuze, in which components had to be able to resist the acceleration to which a projectile was subjected on being fired. Drawing on the experi-

ence gained in the work on the VT fuze, the National Defense Research Committee developed for BRL a small radio transmitter that could be placed in the nose of a projectile in place of its fuze, to send signals back to the firing point as the projectile moved along its trajectory. An antenna, placed behine the gun from which the projectile was fired and pointed along the projectile's trajectory, received the signals from the radio, amplified them, and passed them on to a counter. The data thus provided (time intervals and cycles) were sufficient to determine the projectile's rate of spin, from which velocity could be determined. When the necessary corrections were made for acceleration of the projectile after leaving the muzzle, for recoil of the gun, and loss of spin, a fairly accurate reading of muzzle velocity resulted. When put into use at Aberdeen Proving Ground, the T3 field chronograph gave reasonably satisfactory results. However, it proved to be sensitive to nearby automotive ignition systems and other high frequency sources, and the radio transmitter soon began to show a tendency to fail under normal firing conditions. For these and other reasons, work on the spin chronograph was abandoned in favor of improving the Doppler chronograph.

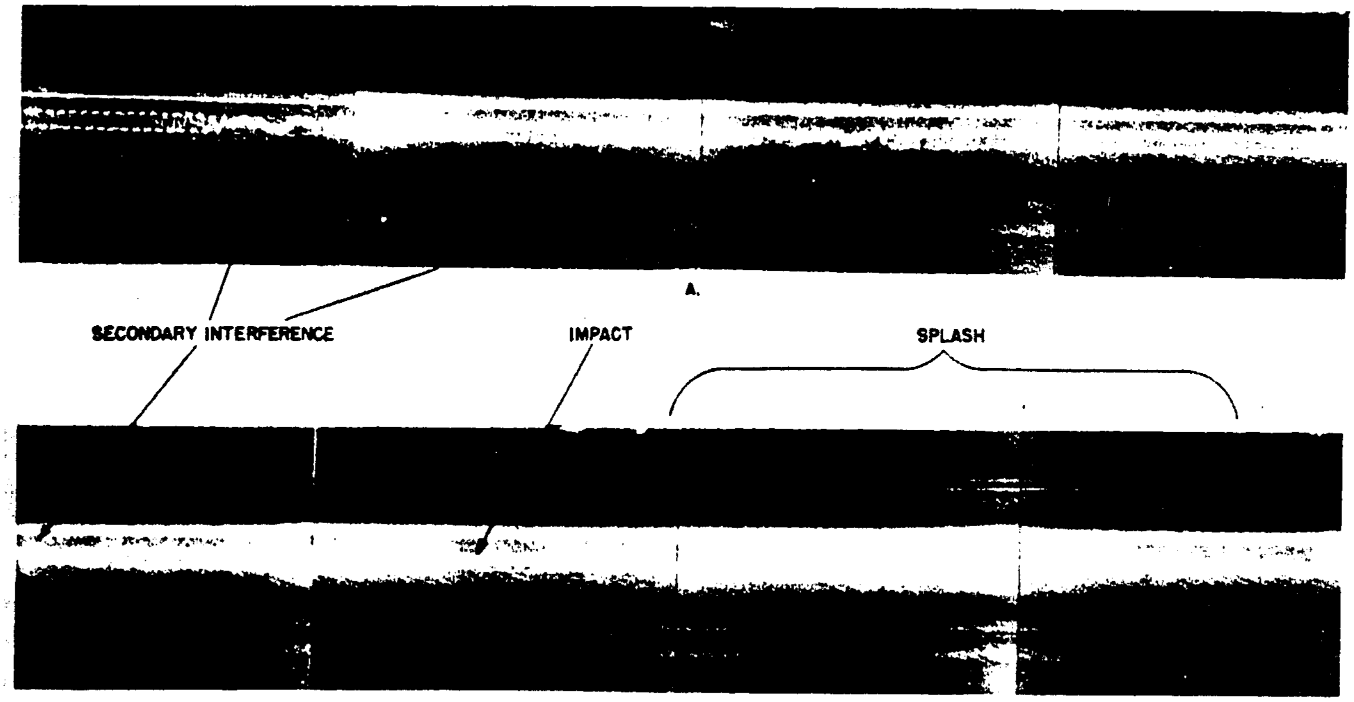
The T4 field chronograph, also called the Doppler chronograph, solved certain problems encountered in the use of the spin chronograph by using only one transmitting and receiving unit, located behind the gun from which the projectiles were fired. The microwave signals sent out by this unit were reflected back to the unit's receiver. The velocity of a projectile was determined by comparing the frequency of the transmitted signal with that of the signal received; the difference between them had a fixed quantitative relationship to the velocity of the reflecting projectile.

Several other chronographs were developed during the war. In 1942, for example, it was found that the velocities of machine gun bullets that had been hand-loaded and fired singly differed considerably from those of the same type of bullets when fired in bursts. In order to account for this discrepancy and make required corrections a machine gun chronograph was developed; by its use the velocity of each round of a burst of up to 200 rounds could be accurately determined.

The last of the new chronographs developed, which was the one most widely used during the last years of the war, was the T6 field chronograph. It used photoelectric *screens* for detecting the passage of a projectile and recorded the times at which it crossed given points along its trajectory. An electronic circuit emitted a sharp pulse of energy when the base of a projectile passed through each *screen,* and this pulse was picked up and transmitted to an electronic counter. The *screens* themselves could be adjusted for either low or high trajectories. The T6 chronograph proved to be quite reliable and, because of its design, offered few problems of maintenance or breakdown; furthermore, it was relatively simple to use, as its *screens* could be projected to any reasonable position desired. Accordingly, seventeen units were built by BRL and, with trained operating teams, were sent to various theaters of operation for use in calibrating guns.

Oscillographs. Because so many of the instruments developed for measuring ballistic phenomena obtained their data in the form of electric signals of only a few millivolts, the oscillograph was developed to amplify these voltages to the potentials desired and record the results. The value of the device depended on its ability to record both short-duration and sustained signals without distortion. On the other hand, its usefulness for many other purposes was determined by the rapidity and ease with which the record it produced could be made available for study. If the data were transcribed on paper, their availability would be limited only by the time needed to record everything required, but records on film had to be processed and could not safely be used until dry. Because of this, film tended to give way to photographic paper, which could be processed much more rapidly. Cathode-ray tubes used in conjunction with photographic paper, and electric styli used with a chemically-treated paper whose color changed as current from the styli traced lines or other marks on it, proved to be very satisfactory in these respects.

The two principal types of oscillographs used at BRL during the war were the Princeton and the Doppler. Units of each type were built into trailers,

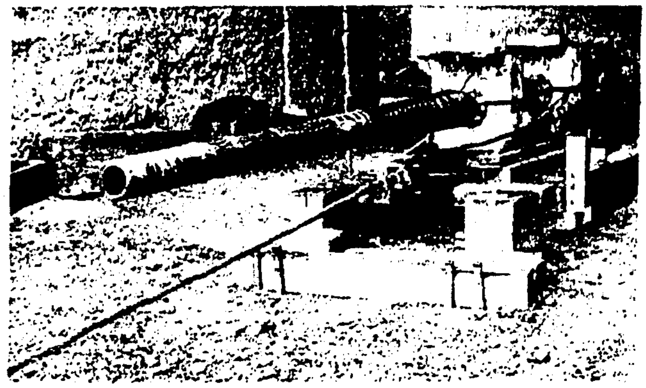


Doppler Oscillograph record of bomb impact in water.

provided with their own generators, and thus made available for use in the field. The Princeton oscillograph was employed chiefly with gauges for recording bomb blast pressures, and the Doppler oscillograph had its greatest usefulness in connection with chronographs for determining velocities, and with other devices for tracing the trajectories of projectiles and bombs. In general, the Doppler was the more adaptable of the two instruments, and was used for recording practically every kind of ballistic measurement.

Pressure and Strain Gauges. The piezoelectric gauge continued in use throughout World War II for measuring chamber and recuperator pressures, trunnion reactions, and thrust; it also was used to some extent for measuring the blast pressures created by the detonation of high explosives. However, until 1943 it was not satisfactory for this last purpose, chiefly because the blast data it provided could not regularly be correlated with the destructive effects of blast as determined by observation. As the field of terminal ballistics gained in importance during the early years of World War II, the need for reliable blast measurements became more and more urgent, so that every effort was made to modify the piezoelectric gauge for measuring blast. The answer was finally found in a new method for preparing the tourmaline crystals which, when compressed, provided the voltage output of the gauge. The successful adaptation of the piezoelectric gauge was completed early in 1943, and at once the instrument opened new avenues for the advancement of terminal ballistics.

At about the same time as the modified piezoelectric gauge was brought into use for blast pressure readings, gauges were obtained for measuring the strains created by propellant gases in the chamber walls and tubes of cannon. The patch-type strain gauge, procured from the Baldwin Locomotive Company in 1943, consisted of a fine wire grid mounted flat on a piece of felt. When cemented to a section of the item of equipment to be tested and connected to leads supplying current to the grid, stress in the item produced by pressure within or outside it was indicated by a proportional change in the resistance of the wire grid; this was recorded by the deflection of a line reproduced directly on a graduated film. This type of resistance gauge was small and could be attached directly to equipment to be tested, without boring holes or using clamps. On the other hand, in the original version the



Patch-type strain gauge [*installation*]

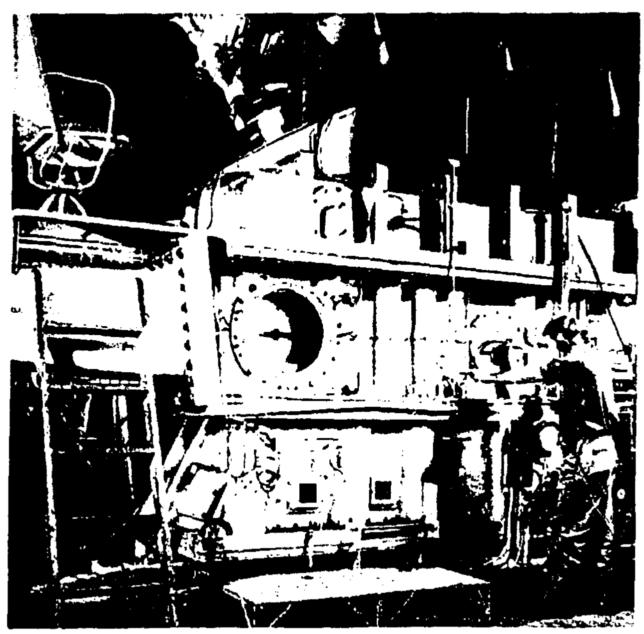
changes in the grid's resistance were of a low order and small changes in voltage had to be amplified, and the grid itself was quite sensitive to changes in temperature; these disadvantages were overcome in the improved models put into use before the end of the war.

The second type of resistance strain gauge, referred to as the CAN type, was developed principally for measuring gas pressures in rocket chambers. It consisted of a resistance element wrapped around a hollow cylinder within a metal housing, and the housing was threaded so that it could be screwed into place within a gun chamber. The gas pressure built up by a burning propellant within the chamber was transmitted to the cylinder and, by the stress it created there, changed the resistance of the wire coil. This was reflected over the leads that supplied current to the coil, and the process of recording this change of resistance as change in pressure was much the same as for the patch-type gauge.

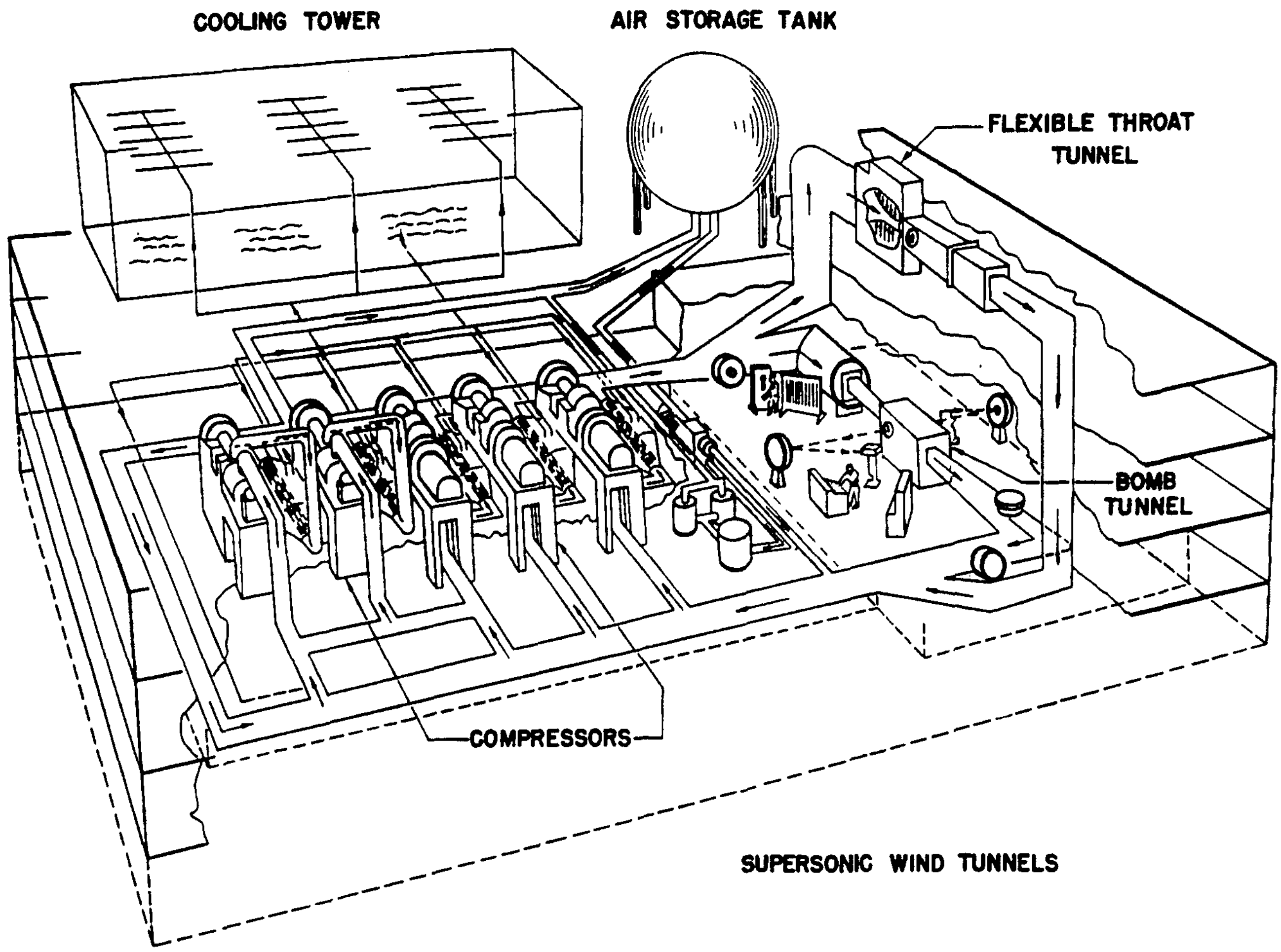
Several other types of gauges for special ballistic measurements were developed during the war, but the piezoelectric and the patch-type and CAN strain gauges were those most generally used.

The Wind Tunnel. In many respects the construction of a supersonic wind tunnel at BRL was the greatest single forward step taken in ballistic instrumentation at the Research Laboratory during World War II. Between the wars six wind tunnels had been built in Europe (two in Germany, one in Switzerland, one in Italy, and two in England) for experimental work in ballistics and aerodynamics, but, apart from the limited facilities of the General Electric Company at Lynn, Massachusetts, and of the National Bureau of Standards at Washington, nothing of the sort had been constructed in this country. The GE and NBS equipment could be used to obtain limited quantities of ballistic data, enough to show clearly the need for more, but nothing could actively be done at BRL to fill this need until 1943. Even the wind tunnel at Wright Field, Ohio, which had been built early in the war and in the summer of 1943 was used by BRL and the Armament Laboratory of the Army Air Force to study 4.5-inch rockets and 500-pound GP bombs, could produce only subsonic velocities. At this time the wind tunnel at Peenemunde, the great German guided missile development and test center, was producing velocities as high as three times the speed of sound.

In 1940 Professor von Karman of the California Institute of Technology, who served during the war as a member of BRL's Scientific Advisory Committee, recommended the construction of a wind tunnel at Aberdeen Proving Ground for Ordnance Department ballistic research, and proposed that it be able to produce both subsonic and supersonic velocities. Shortly thereafter the Guggenheim Aeronautical Laboratory of the California Institute of Technology designed such a tunnel that was able



Supersonic wind tunnel being adjusted to present different aspects to the on-rushing air by means of a mechanical linkage operated by the man on top of the tunnel.



Flow diagram of supersonic wind tunnel

to produce velocities up to Mach 4.3. The project for the Ordnance Department was pushed vigorously, but it was not until the fall of 1943 that construction began, and the tunnel was not ready for use until November 1944. Fitted with subsonic and supersonic nozzles, the latter being able to produce velocities up to Mach 1.7, the BRL tunnel was promptly put to work to obtain basic design information and data for use in developing and modifying bombs, rockets, and other fin-stabilized projectiles. The advantages afforded the designers by the new facility were enormous, and rapid progress was made in the field of fin stabilization.

Meanwhile, construction began of a ballistic tunnel that would produce velocities up to Mach 4.4, for use in the study of spin-stabilized projectiles. However, this was not completed until after the end of the war.

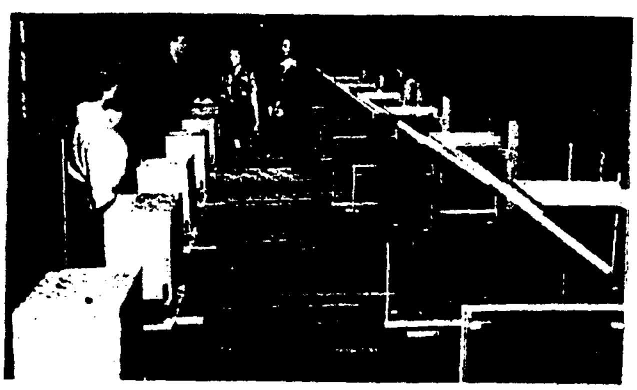
The Aerodynamic Range. Accurate observation of the behavior characteristics of fast-moving objects is essential to progress in many fields of science and technology but is complicated by the fact that the human eye cannot see clearly the details of objects moving more rapidly than 60 fps. For this reason, for many years attention had been given to the development of instruments by which rapidly-moving objects could be *stopped* on photographs, so that their characteristics in motion could be studied. High-speed photography had been successfully developed by 1940, but not far enough for ballistic purposes; on a photograph taken at even 1/10,000 of a second — the best that could be done at the beginning of the wartime period — a caliber .50 bullet appeared as a 4-inch blur. It was not until ultrahigh-speed photography, with exposure times as brief as 1/1,000,000 of a second, was

developed in the early 1940's that much use could be made of this procedure in advancing the science of ballistics.

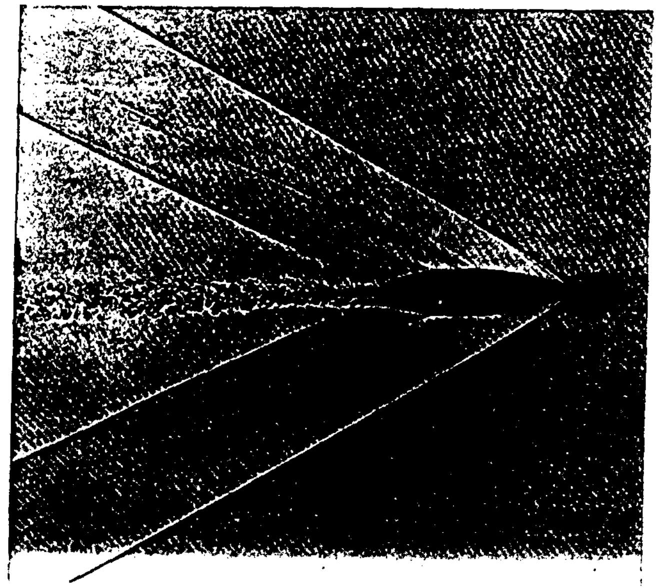
Spark photography made possible the new development. Taking still pictures of a moving object by a single flash of light had been introduced in the middle of the nineteenth century and had proved practicable. The first spark photograph was made in 1851, when an unblurred picture of a newspaper clipping attached to a revolving drum was obtained by use of a spark from a Leyden cell. Great improvement had been made since the first experiment, of course, but what was needed for ballistic purposes was a series of photographs of a projectile in flight, sufficient in number so that the entire sequence of its behavior characteristics could be studied. The aerodynamic range at BRL was completed for this purpose in early 1944; the designers experimented with two major techniques — spark and microflash photography — to obtain the desired data.

Spark photography required the passage of a projectile between a light source and a photographic plate or film; the light cast a shadow of the projectile on the sensitized surface. Microflash photography, on the other hand, employed a light source to illuminate the projectile so that it could be photographed. Of the two, the spark technique appeared to promise the greater accuracy, and it was chosen for use in the aerodynamic range.

There were three basic requirements for obtaining a spark shadowgraph: (a) a light source 1/1,000,000 of a second in duration and of sufficient intensity to expose a photographic plate or film; (b) synchronization of the triggering of the light source with the passage of the projectile to be photographed; and (c) no interference with the free flight of the projectile. The electrostatic charge induced in a projectile in flight was used to trigger each successive spark mechanism. This electrostatic charge phenomena was first observed by researchers at Frankford Arsenal, Philadelphia. A series of cameras was placed to record the shadow of the projectile as it passed each; a drum chronograph and electronic counters were added to record the time intervals between photographs. The range itself was 300 feet long.



BRL Aerodynamic Range



Sample of aerodynamic range shadow spark photograph.

Accurate interpretation of the data obtained required a considerable amount of analytical work. From a set of fifty photographs of a single projectile in motion, for example, the spatial coordinates of the projectile and the orientation of its longitudinal axis to its trajectory had to be computed. Within a short time after the aerodynamic range had been put into use the procedure for reducing data to usable form had been developed and refined.

The size of the range limited its use to high-velocity projectiles 20-mm and less in caliber and low-velocity projectiles 37-mm and less in caliber. Scaled-down models were used to test artillery shell and bombs.

Shadowgraphs of projectiles traveling at supersonic velocities revealed in minute detail the shock wave patterns they created. Inasmuch as the characteristics of a shock wave depended on the

velocity of the projectile producing it, it was possible, after a considerable quantity of data had been accumulated and analyzed, to determine velocities directly by reference to shock waves. Despite the complexities of the mathematical problems raised, a procedure for this purpose was worked out by which velocity measurements assumed to be accurate within 1 percent were obtained.

Motion Pictures for the Study of Rockets in Flight. The introduction of the rocket in the early years of World War II created radically new exterior ballistics problems that had to be solved if the rockets developed were to be satisfactory for combat use. The flight of a rocket consists of two phases, a burning period, characterized by rapid acceleration, and the period after the motor's burnout, characterized by gradual deceleration. Stability and the other ballistic characteristics of a rocket may differ greatly between these two phases. Furthermore, rockets still in the experimental stage generally have a large dispersion, which can be reduced only in succeeding prototypes by design modifications based on knowledge of the velocity and trajectory of the individual experimental model.

As these problems were examined, it became apparent that the motion picture camera met most of the requirements to obtain the data needed for solving the various problems of the exterior ballistics of rockets. When first used for this purpose in 1943, its precision was found to be more than sufficient. Furthermore, as the techniques for recording the flight of rockets by cinematography were developed, they were also applied to the study of other projectiles.

Using conventional motion picture cameras placed several hundred feet from the line of a rocket's flight at properly selected points along it, the series of pictures produced provided most of the information required for plotting trajectory and determining mean velocity. The rest of the data needed for these purposes was supplied by the chronographic equipment tied in with the cameras. The records so obtained demonstrated not only acceleration and deceleration during the two phases of a rocket's flight but also permitted measurement of yaw.

Motion pictures first were used to record ground firings, and it was found that a camera placed directly behind a launcher and fitted with a suitable chronograph could track a rocket through its burning phase and also record the point and time of its impact on a target. By the summer of 1943 this part of the procedure for recording ground firings had been perfected, and the next step was to adapt it to record the firings of rockets from aircraft. As experiments accumulated, the procedure was also applied to the study of mortar shell, range, dive and skip bombing, and turret firings, all with great success.

The Ballistic Camera. All bombing tables prepared before World War II had been based on experimental range bombings by aircraft flying at maximum altitudes of 25,000 feet and maximum speeds of 180 mph; the camera obscura system was used to obtain the needed data. However, when bombers that operated at much higher altitudes and greater speeds were put into combat, the camera obscura system could no longer be used effectively to get the data for determining bomb trajectories and probable points of impact. A new system, called the ballistic camera system, was devised to do the job.

As first devised in 1941, the ballistic camera system was for use at night. It consisted of several cameras properly placed to locate and record the flashing lights of an approaching aircraft and the signal indicating its release of a bomb. The rotating shutters of the cameras were synchronized so that the required time data were provided. A system of interconnected motion picture cameras and pressure gauges located and recorded the bomb's point of impact.

When a flash lamp containing a high-intensity light source was developed, it was possible to use the ballistic camera system for daylight trials as well. The accuracy of the system was increased by adding geophones for detecting the seismic waves produced when a bomb hit the earth, by refining the system of signaling between aircraft and ground points, and by perfecting the synchronization of the camera's shutters.

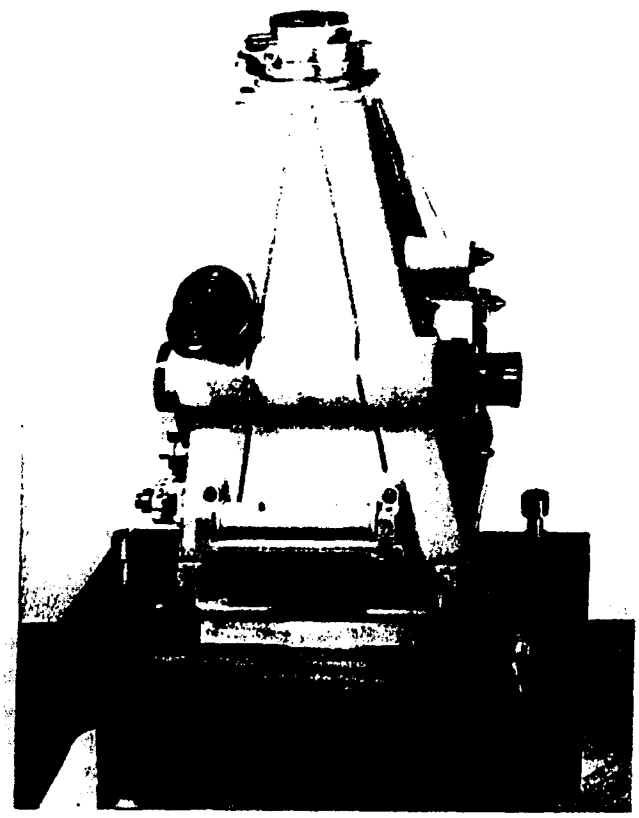
Although it was a very involved combination of photographic, signaling, gauge, and recording equipment, the ballistic camera system provided

data whose accuracy met all the requirements of bombing tables. Because of its early success, BRL constructed two mobile stations for use by the Aberdeen Bombing Mission at Muroc Lake, California, and the Army Air Force at Eglin Field, Florida. The system was sufficiently adaptable so that in the postwar period it was used successfully in the study of guided missiles.

INTRODUCTION OF ELECTRICAL AND ELECTRONIC COMPUTERS

The new ballistic instruments put into use at BRL as the war progressed, together with those that were on hand when the war began, produced ever increasing quantities of ballistic data, all of which had to be analyzed before they could be applied to the solution of research problems or used in the preparation of the innumerable firing and bombing tables required. Because this analysis was time-consuming, the Laboratory kept a close eye on the development of new computing machines and obtained new equipment as it was released for use.

The Bush differential analyzer, acquired in 1935, lived up to its characterization as *the most important tool acquired before the Ballistic Research Laboratory was formed,* but it was unable to keep abreast of the work it was called upon to do. Accordingly, BRL arranged to have access to a larger analyzer of the same type in the Moore School of Engineering at the University of Pennsylvania. Rather than move this machine to Aberdeen Proving Ground, a staff was sent to Philadelphia to operate it for BRL. To the advantages gained by this action was added the opportunity to have new personnel trained in the use of the analyzer by staff members of the school who were thoroughly familiar with the machine. At the same time, considerable progress was made in substituting electrical for mechanical components in the Philadelphia analyzer to obtain greater speed of operation; also, modifications of operational procedures were made to increase flexibility and accuracy as well as speed of both analyzers. The success attained in this work is best summarized by quoting from a report on the modified analyzers that covered the first six months of work of 1945:



Goerz camera and leveling table used in ballistic camera tests.

The new equipment not only gives a high degree of accuracy on test runs, but also permits considerably higher operational speed than the previous set-up. Between 1 February 1945 and 30 June 1945, the Aberdeen Analyzer alone computed 1560 production trajectories used in the preparation of ten firing tables. This work was in addition to test runs and certain theoretical work carried on during this period.

In addition to the improvements made in the mechanical integration analyzers, electrical calculators of various types were procured by the Laboratory to assist in the work to be done. Also, much thought was given to the development of electronic computers.

Punch-Card Machines. In 1937 Colonel Zornig became interested in the possibility of using electrical calculating machines for ballistic computation. This interest was intensified when

members of the Laboratory's staff visited the International Business Machines Corporation in 1938 to compare a firing table computed automatically with one that had been prepared by the older procedure. The IBM table was found to contain only a few errors, none of which was consequential, and it was decided at once to procure punch-card machines for ballistic work. However, shortage of funds and difficulties in obtaining the machines delayed the acquisition of the equipment until 1941, when an alphabetical tabulator and a multiplier were delivered. In the next two years a number of additional punch-card machines, most of them fitted with special attachments to better adapt them to ballistic work, were received.

At first this equipment was used almost exclusively for the preparation of firing tables, the procedure for which was standardized and involved a number of repetitive operations. The machines performed one operation, checked the results, and then went on to the next step. As experience in their use was acquired, they were put to work on other problems, such as those involved in the theory of breech rings, fuze-setting coefficients, shock waves study, and probability integrals.

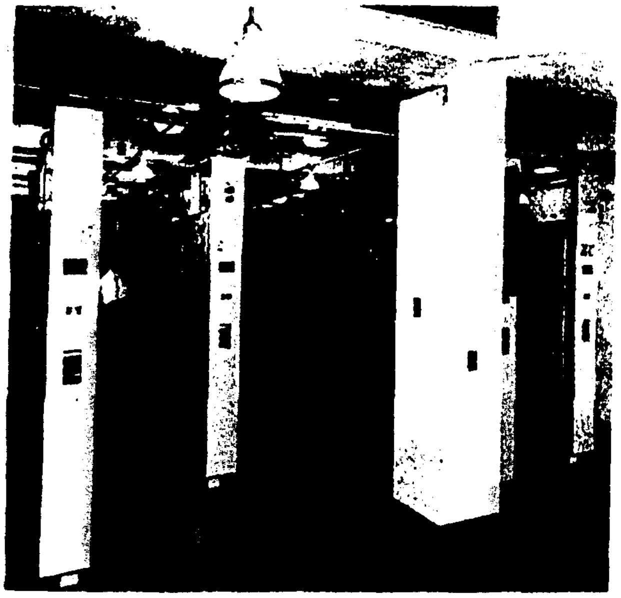
For all of its advantages, the punch-card system proved fallible, and the rectification of errors required more time than anticipated. Furthermore, as the form of firing and bombing tables was abbreviated, the need for this special type of equipment was somewhat reduced. In an effort to obtain a machine of this type that would have a much higher operating rate, members of the BRL staff worked closely with representatives of International Business Machines Corporation in the design of the relay calculator, two units of which were procured by BRL in the fall of 1944. This new

Punch-card equipment being used for ballistic computations.

calculator added and subtracted at twice the speed of the standard punch-card machine and multiplied two six-digit numbers in 0.15 second, as compared with the 4.8 seconds required by the standard multiplier; however, it still proved too slow for practical use. Karl Kempf, in his *Historical Monograph on Electric Computers Within the Ordnance Corps*, gave an account of BRL's use of the relay calculator:

> *The two IBM Relay Calculators were used for a short time but they were not successful. Two Bell Relay Computers were used. They were accurate, but slow and required expert maintenance. Dust and humidity adversely affected their operation. However, many useful results were obtained from the twin Bell Computers during their years of operation. One good feature of the Bell machines was that they would run 16 hours unattended, overnight. A problem regularly would be placed on the computer at 4:00 PM. The next morning, arriving operational personnel would find the problem solved and the machine waiting, or the machine still feverishly running the problem to a successful conclusion. Many times, if it was believed that the machines would complete a problem during the night, a new problem was set before the machine for it to tackle until personnel arrived the next morning. This mode of operation increased the productivity of the computers with a minimum of personnel. Once in a while, a dirty relay contact would cause a stoppage, for the Bell Computers would either run without error or not run at all.*

Development of ENIAC AND EDVAC. What was needed to solve BRL's increasing problem of ballistic computation was a computer of great speed, high accuracy, and maximum flexibility of operation. To obtain such a device two electronic computers were designed in the latter part of the war, but their development was not completed until after the war ended and the account of their usefulness to the Laboratory belongs to the postwar period. Named the ENIAC (electronic numerical integrator and computer) and the EDVAC (elec-



Bell Relay computer, showing racks in which the computing, storing and controlling relays were mounted.

tronic discrete variable computer), they were built by the Moore School of Engineering of the University of Pennsylvania.

The ENIAC was a large U-shaped cabinet of forty-two panels which contained 19,000 vacuum tubes and 1,500 relays. The panels were grouped in thirty different units, each of which performed one or more mathematical functions. The accumulators added and subtracted, another unit was responsible for multiplying, and a third divided and obtained square roots. The computed answers were transferred to punch cards by the printing unit of the computer. The relatively high speed of the ENIAC is indicated by the fact that an accumulator required only 0.0002 second for an addition or a subtraction; the multiplication of two ten-digit numbers required 0.028 second.

During the latter part of the work of designing the ENIAC, it became apparent that the development of a different type of electronic computer, more flexible and better able to store numbers, would be advantageous and entirely feasible. The invention of a new memory device early in 1944 by Eckert and Mauchly, the designers of the ENIAC, provided a means for obtaining large storage capacity with comparatively little equipment. Accordingly, plans were drawn in July 1944 for the development of the EDVAC.

The ENIAC and the EDVAC had little in common beyond the fact that they were both electronic digital computers. The EDVAC needed fewer channels to perform the same functions and its switching equipment was considerably simplified. It had a memory capacity for approximately 1,000 ten-digit numbers; the ENIAC could accommodate only 20. Finally, the EDVAC could change from one type of problem to another automatically, changes could be made on the ENIAC only by resetting many switches and plugging in different connecting cables.

Even though neither the ENIAC nor the EDVAC was ready for use before the end of the war, they must be regarded as wartime contributions of BRL and the Moore School of Engineering to the advancement of the science of ballistics.

The installation of the ENIAC in 1947 at the Ballistic Research Laboratories marked the beginning of the widespread use of electronic computing machines. Investment rates in computing equipment in the United States rose from the ten million dollars per year in 1953 to one hundred million dollars per year in 1956. By 1961, expenditures for computing equipment passed the billion dollars per year mark. *

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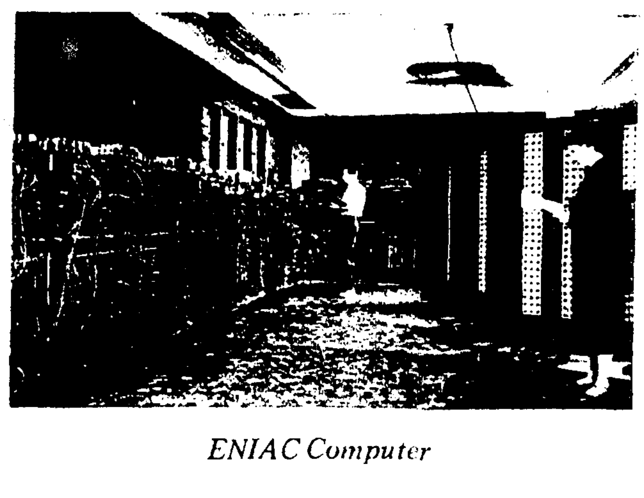
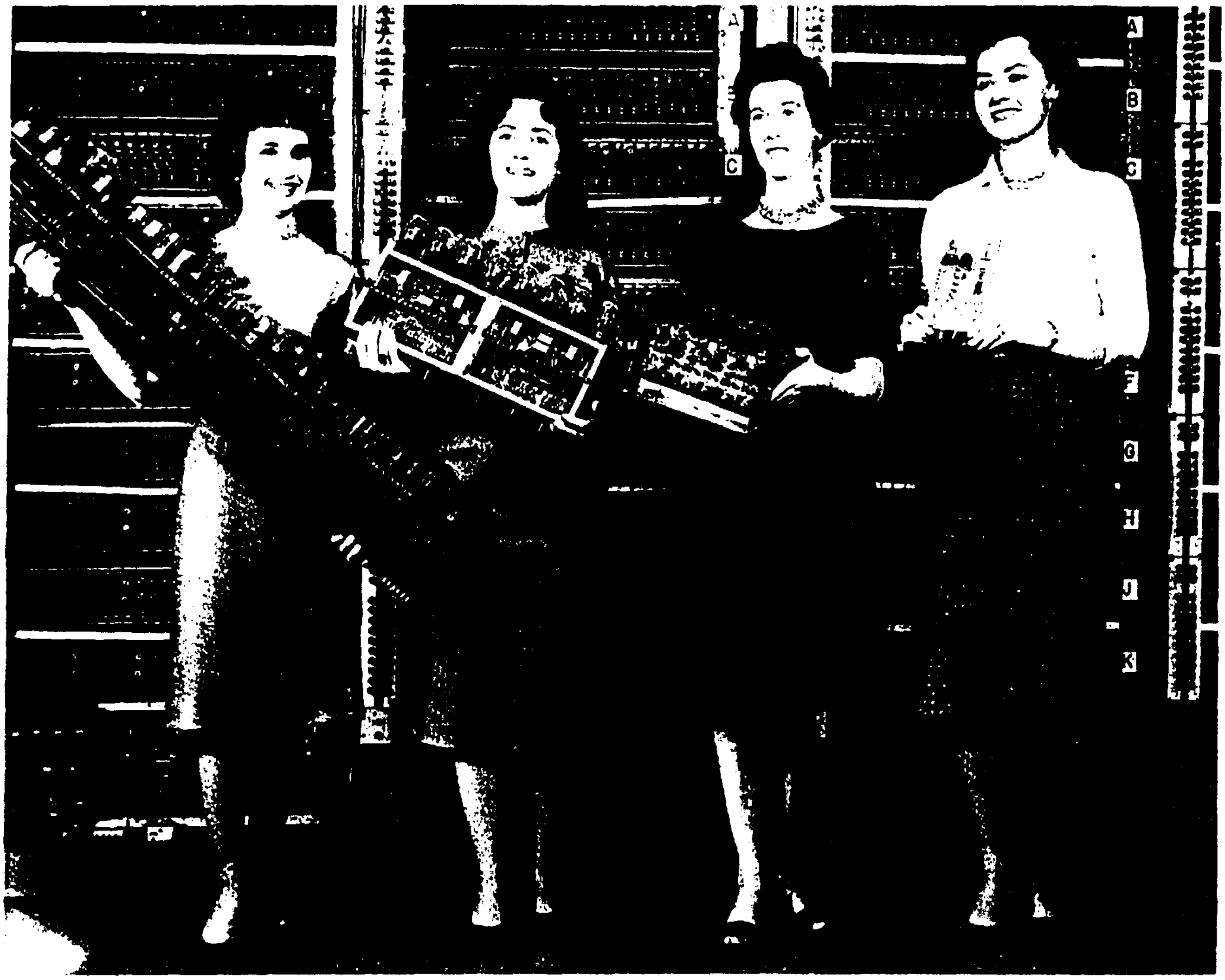
*From the *Historical Monograph, Electronic Computers,* by Karl Kempf, November 1961.



ENIAC Computer



"Evolution of the circuit:" At left is the original ENIAC decade counter circuitry. Second from left is the EDVAC serial adder; then the ORDVAC parallel adder; and finally, at right, is the BRLESC standard circuitry package.

During the war, in the field of interior ballistics most of the attention continued to be devoted to basic research, whereas in exterior ballistics the more pressing problems were those involving weapons and ammunition — what the men at BRL called *quick fix* problems. Nevertheless, impressive advances were made in both fields.

INTERIOR BALLISTICS

BRL's wartime work in interior ballistics had two principal objectives, namely, increasing knowledge of the fundamental processes of interior ballistics as a means of improving the design of new guns and the performance of those already in use, and developing more accurate procedures for predicting the performance of a gun under given conditions. Successful work toward these ends enabled the Ordnance Department to obtain higher and more uniform muzzle velocities, to improve the ignition of propellants and thereby eliminate hangfires, to reduce barrel erosion, to reduce muzzle flash and smoke, to develop propellants with longer storage life, to reduce the weight of guns generally, to protect gun mounts against muzzle blast, and to improve the performance of recoil mechanisms.

If a gun can be described as a single-stroke heat engine whose fuel is a projectile's propellant, then the basic research in interior ballistics conducted during the war can be said to have centered on the fuel problem. Applied research, made possible for the most part by improvements in the *fuel* and a great deal of new knowledge about its performance characteristics, was directed toward improvement of the *engine* as a whole. Such basic research carried on in the *engine* field dealt with such phenomena as heat loss through the walls of chamber and tube, friction during and after the engraving of a projectile, and general gas friction; however, these problems could be finally solved only after extensive experiments had been conducted, and after the war had ended.

In particular, studies made of the physical chemistry of propellants had valuable practical application. Sufficient new knowledge was obtained of the process of ignition to make possible the development of greatly improved propellants of several types; this progress was especially useful in the development of rockets. Hangfires in guns and the *chuffing* of rockets were virtually eliminated. Studies of the flow of gases through erosion vents aided considerably in the development of satisfactory nozzles for recoilless rifles. Finally, advances in the theory of interior ballistics led to the formulation of new methods for constructing interior ballistics tables.

Propellants. The burning of a propellant and the thermodynamic qualities of the powder gases it produces depend not only on the quantity of the propellant used but also on the geometric form and thickness of its grains. One of the major phases of the interior ballistics research at BRL during the war dealt with the related problems of the rate of burning and the equilibrium or static properties of the powder gases produced. Because very little was known about the details of the burning process, all phases of these problems were thoroughly studied. The production of carbon monoxide, carbon dioxide, nitrogen, water vapor, hydrogen, and, under special circumstances, small amounts of other gases, as the end products of ignition was verified in detail and every effort made to determine how these gases were produced. Experiments with nitrocellulose by no means completed everything that was to be done, but enough was learned to make possible the development of improved propellants, catalysts for propellants, and methods of eliminating the various ignition difficulties that had occurred in guns and rockets.

One of the more important outcomes of this research in the physical chemistry of propellants was the development of an end-burning powder grain in stick form which had major advantages over the small-grain nitrocellulose type of propellant when used for large-caliber rocket motors. The new propellant contained neither nitrocellulose nor nitroglycerine; it depended on the combustion of either powdered aluminum or powdered graphite in combination with powdered titanium, with potassium chlorate as the source of oxygen, for propulsive force. This mixture was embedded in a resinuous matrix which, when softened by heating, could be forced directly into the casing of a rocket motor. It was believed that this composite propellant would perform more satisfactorily than a nitrocellulose propellant throughout a wider tem-

perature range. However, although a 35 percent increase in velocity was obtained when bazooka rounds were fired with it, the pressures developed were too great for small rockets. As a result of the work done on this problem at BRL, composite propellants were developed which are now used as single-grain motors 6 inches or more in diameter for large rockets.

Other applications of the findings of research in the physical chemistry of powders included the treatment of nitrocellulose propellant by immersing its grain in a boiling 2 percent aqueous solution of p-phenylene-diamine for forty minutes and removing the grains from the solution and drying them at 50°C for several hours. The grains so treated burned much better than those not treated, for the flame spread very rapidly over all their surfaces.

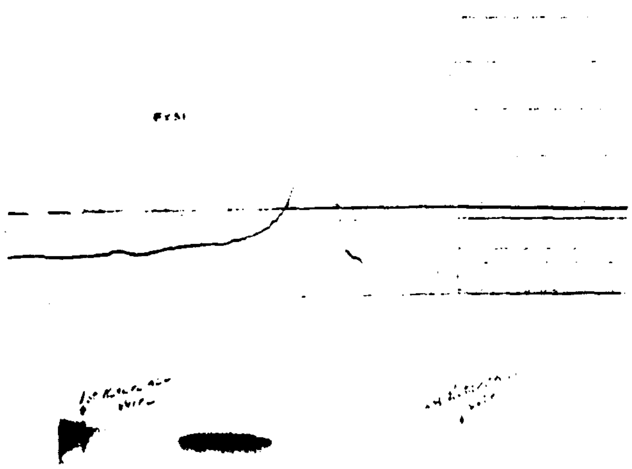
Research on propellants also provided information valuable to the groups working to reduce bore erosion and the bad effects of muzzle heating. A special application to a new weapon was in connection with the development of recoilless rifles. It was found that the throat of the nozzle through which the powder gases escaped to the rear of such a weapon tended to suffer severe erosion, the result of either the metal melting under the very high temperatures created or the chemical action of the powder gases themselves. Investigations indicated that the factors responsible for the melting of the metal were the coefficient of heat transfer from the powder gas to the walls of the vent, the melting point and thermal diffusibility of the metal, the shape of the vent, and the flame temperature of the powder. It was also found that the main reaction resulting in chemical erosion was that between iron and carbon monoxide, for which the sulphur in the black powder of the igniter acted as a catalyst. With this information at hand, the use of either a cooler powder or a metal with a higher melting point was proposed to prevent the melting of the nozzle's throat, and removal of sulphur from the black powder was suggested to prevent chemical corrosion; when this latter step was taken, chemical erosion was reduced by 60 percent.

Movement of Powder Gases. Important relationships exist between the flow of powder gases within the chamber and tube of a cannon and the cannon's recoil; further investigation of the behavior of powder gases became increasingly necessary as high-velocity guns were developed. Accordingly, theoretical investigations were conducted to supply the needed information about the behavior of powder gases. These included studies of the flow of gas through vents in conventional artillery and the nozzles of the recoilless rifles being developed, and also after a projectile had left a cannon's muzzle. This last problem was closely related to the problem of recoil, which, although of secondary importance to interior ballistics, was of primary importance to the design of recoil mechanisms.

Interior Ballistic Trajectories. In interior ballistics the trajectory of a projectile as it moves from its original position in a cannon's bore to and out of the cannon's muzzle consists of the actual movement of the projectile plus the variations in gas pressure, velocity pressure, and rate of travel as related to the growth of gas pressure. Such an interior ballistics trajectory can be specified by curves of pressure and velocity to which are added data about the maximum gas pressure exerted, distance of travel at maximum gas pressure, distance of travel after the propellant has completed burning, and other relationships between the movement of the projectile and the burning rate of the propellant.

A considerable amount of theoretical work was done on this problem of interior ballistic trajectories; special attention was given to the forces that affect a projectile's acceleration, and some of the theoretical work was supported by experiment. The early investigations of the movement of projectiles within cannon used piezoelectric and strain gauges, but toward the end of the war X-ray photography was used to obtain 1-microsecond pictures of projectiles in motion. By taking X-ray pictures of identical rounds at different intervals after firing, the data for complete pressure-time curves were obtained. The procedure thus developed proved to be especially useful in verifying or correcting similar curves derived theoretically.

Muzzle Ballistics. Muzzle ballistics, a field of inquiry on the border line between interior and exterior ballistics, was given some attention be-



Lower: X-ray view of projectile in gun barrel
Upper: Pressure-Time Curve

cause of the effects powder gases produce as they emerge from the muzzle of a cannon. Although the gases at this point still exert force on a projectile, their greatest significance lies in the fact that they can also produce flash and smoke around the muzzle. These phenomena had to be reduced because of the danger that they would reveal the location of a cannon to the enemy and at the same time obscure the target and thereby reduce the rate of fire.

By study of both still and high-speed motion pictures, it was found that muzzle flash consists of muzzle glow and primary and secondary flash. The sources of each having been determined, (for example, the reaction of the hydrogen and carbon monoxide of the powder gases with the oxygen of the air was found to be the major cause of primary flash), it was possible to plan means of overcoming muzzle flash. Comparable research increased somewhat the knowledge of the exact way in which the chemical composition of propellants caused smoke at the muzzle of a cannon. The problem, however, was to reduce flash and at the same time keep smoke to a minimum, for changing the composition of a propellant to reduce or eliminate the one phenomenon invariably seemed to increase the probability of maintaining or intensifying the other. However, the information accumulated was best employed by designing flash suppressors to be attached to the muzzles of guns and by changing the composition of propellants to reduce the amount of smoke they produced.

EXTERIOR BALLISTICS

BRL's wartime program for research in exterior ballistics, conducted under the leadership of L. S. Dederick with the aid of F. V. Reno and A. C. Charters, was directed for the most part along applied lines. Its principal objective was the obtaining of additional information that would assist in (a) the development of projectiles of greater ballistic efficiency, (b) the preparation of firing and bombing tables and other devices to improve the fire control of new weapons (and many of the older ones already in use), and (c) the improvement of general firing techniques and fire control methods. In order that these objectives might be attained, knowledge of the behavior of projectiles in flight had to be expanded. The immediate overall purpose of the program, of course, was to increase the accuracy of weapons as much as possible.

The wartime efforts of the exterior ballistics group were directed toward refining the available data on both projectile motion and airflow, in which the wind tunnel, the aerodynamic range, and the ballistic camera were used to check the data already on hand and to add to that store.

Projectile Motion. Certain aspects of the behavior of projectiles, and especially of rockets, in flight suggested a re-examination of the findings of Fowler, Gallup, Locke, and Richmond, which for two decades had been used as a frame of reference for the analysis of data and the preparation of firing tables. These English ballisticians had assumed that the only major factors affecting the behavior of a projectile in flight were drag, lift, and the moments of overturn, damping, and deceleration of spin. They had tacitly ignored the effects of the so-called Magnus force. This phenomenon, produced by the interaction of a projectile's spin and yaw, acts in a direction perpendicular to the plane of the yaw; it has been compared to the force that enables a pitcher to put a curve on a pitch. Noting certain discrepancies between the behavior of spinning projectiles as calculated and as observed experimentally, the ballisticians at BRL concluded that the Magnus force must be taken into consideration in exterior ballistic calculations.

The theory of the behavior of finned projectiles (including bombs and rockets) also was re-examined by means of wind tunnel experiments, but pressure of other duties made impossible any conclusive findings during the wartime period. Enough was learned, however, to realize that the general theories of the motion of projectiles did not adequately cover the case of finned projectiles. This had certain interesting implications. For example, it was originally believed that a finned bomb would have better stability if it did not spin at all, but it was now ascertained that a slow rate of spin reduces the effects of a force that acts upon it perpendicular to its trajectory. Rockets also were found to be a special case in that allowances had to be made for the aerodynamic results of the changes in weight that accompany the burning of the motor and the streaming of exhaust gases through the nozzles.

Much of the work on the motion of projectiles was possible by use of the wind tunnel after it went into operation in 1944. However, although the measuring of forces in the wind tunnel was a relatively simple and direct problem certain inadequacies were noted in the data obtained. These resulted principally from inability to reproduce in the wind tunnel the aerodynamic forces that operate on a projectile in free flight through the air. Compensation was provided by comparing the behavior of projectiles in free flight with their behavior in the wind tunnel, and weighting the wind tunnel data in accordance with the findings of the comparison.

With the completion of the aerodynamic range in 1943, spark photography also became available and was used to supplement wind tunnel tests. In general, it rendered yaw cards obsolete as a means of measuring aerodynamic coefficients. Through the accuracy of the range, it was possible for the first time to obtain valuable data on the motion of a projectile about its center of gravity. This was accompanied by data on the motion of a projectile's center of gravity relative to the projectile's mean trajectory.

Airflow Around Projectiles. By the time World War II was well under way, exterior ballisticians had to deal with projectile velocities greater than the speed of sound. At these velocities projectiles *pile up* air ahead of them, producing shock waves. Investigations demonstrated that such shock waves were the predominant influence affecting the flow of air around a high-velocity projectile, which in turn affected the projectile's behavior in flight. Accordingly, study of these shock waves quickly became a program of major importance in exterior ballistics. All the information that could be obtained was needed, for detailed knowledge of the airflow pattern would make possible improvements in projectile design by which optimum performance could be obtained.

Toward the end of the war Dr. von Neumann, of BRL's Scientific Advisory Committee, suggested a *wavelet* theory on which a procedure for determining total airflow around a high-velocity projectile could be based. It had been noted that exceptionally good spark photographs of high-velocity projectiles in flight showed wavelets originating at different points on the surface of the projectile, behind the shock wave (and apparently caused by slight irregularities on the surface). When the peculiar shape of each wavelet was carefully examined and the information derived from the complete study put together, it was possible to determine the general characteristics of the flow of air around the projectile.

The Ballistic Performance of Projectiles. All firing tables prepared by the Laboratory before 1943 depended on a limited number of *standard* drag functions and drag coefficients which had been worked out for generic types of projectiles between the wars. Whenever a drag function was needed for a projectile of new design, the function already established for the type of projectile most closely resembling the new design was used. By 1943, however, the use of solenoid chronographs in conjunction with electronic counters made possible the rapid and accurate calculation of drag functions for new projectiles on a fully experimental basis. When these data were used in the preparation of firing tables and these tables were compared with others based on the old *standard* drag functions, the advantages of the new procedure were clearly evident.

The solenoid chronograph-electronic counter combination was also used to obtain information about other aspects of the behavior of projectiles in

flight. For example, experiments were conducted to determine whether surface roughness had any significant effect on drag, to find the coefficients of cross-wind forces, and to observe the damping effects of maximum and minimum yaw.

The Matching of Projectiles. So long as machine guns were used principally against stationary or relatively slow-moving ground targets, it was not necessary to prepare separate firing tables for each type of the ammunition — ball, armor-piercing, incendiary, and tracer. A single firing table was sufficient for all types; the range scales on the open sights of the guns were used to make corrections for types of ammunition as well as for elevation and azimuth. When machine guns came into general use as part of the armament of combat aircraft, however, this situation was changed radically. Not only was the new target of extremely high speed, placing a premium of specific knowledge of time of flight, but also the cross winds at combat altitudes had considerably greater effect on the flight of bullets than did their counterparts on the ground.

To obtain information to solve the problem of aircraft machine gun fire, in 1940 Colonel Simon, the Director of BRL, began a series of tests to determine the behavior of bullets fired from the sides of moving aircraft. To obtain statistically reliable results a typical experiment called for as many as nine passes in each of which a 40-round mixed burst was fired. After each experiment, the machine gun was removed from the aircraft and fired indoors, to check its muzzle velocity. The experiments were conducted with both caliber .30 and caliber .50 ammunition of armor-piercing, incendiary, and tracer types. The three types had measurably different deflection characteristics when fired sidewise from a moving aircraft. In order to correct this situation and obtain uniform deflection, it was recommended that the ballistic coefficients of the three types of round of each caliber should be made uniform.

These experiments also revealed that lots of the same ammunition made by different manufacturers often had different ballistic coefficients, and steps were taken to remedy this.

Meanwhile, the Navy Department had been working on the same problem of matching aircraft machine gun rounds and, because machine gun bullets were small and therefore not so susceptible as artillery projectiles to inaccuracies resulting from variation in the ballistic coefficient, had concluded that effectiveness of machine gun fire from aircraft would best be obtained by matching times of flight (that is, by assuming uniform muzzle velocities for all three types of bullet). Further study by BRL indicated the merits of this conclusion. The outcome was the adoption of a common policy by the Ordnance Department, the Army Air Corps, the Navy, and the British Services, that called for all machine gun bullets of a given caliber to have the same ballistic coefficient or, should this be impracticable, to have the same muzzle velocity.

TERMINAL BALLISTICS

Before the end of the war the new field of terminal ballistics was established as a third major area of ballistic investigation. Although an effect-of-fire program had been initiated at BRL in the latter part of the period between the wars, the costs of comprehensive tests needed for rapid progress in this field were too high for peacetime budgets. Accordingly, only limited laboratory experiments and small-scale tests were carried out to obtain information about such phenomena as the number, sizes, and velocities of the fragments produced by detonation of HE shell and bombs. Even so, the data obtained were useful; what is more important, however, is that the need for specific information about the performance of projectiles on hitting their targets was recognized as essential to the continued development of ballistics and the general improvement of weapons. Until this time, it had been assumed that the delivery of a projectile onto its target, together with a reasonably high probability that it would detonate, was sufficient for all practical purposes.

The viewpoint represented by this initiation of effect-of-fire investigations at BRL was given strong support by reports of the performance of high-explosive ammunition in the early years of World War II. Targets as large as cities were not effectively neutralized by the impact of hundreds of bombs dropped by enemy bombers, and small well-protected targets, such as concrete-and-steel pillboxes, were destroyed only if hit by many HF shell at approximately the same spot. Information

of this sort stressed the need for improving the performance of projectiles and bombs on reaching their targets.

The trend toward greater emphasis on this phase of ballistic investigation was given recognition when BRL was reorganized in mid-1942, at which time the name of the Effect-of-Fire Section of the Interior Ballistics Branch was changed to Terminal Ballistics Section. A year later this section was withdrawn from the Interior Ballistics Branch and raised to branch status. The new branch had as its mission the study of the performance and effects of projectiles and bombs on reaching their targets. It was expected that the findings of this program would not only aid in increasing the effectiveness of our own and our Allies' weapons but also that they would throw light on such problems as the types of armor plate, bomb shelters, fortifications, and other defense measures that would be most effective for the protection of our forces.

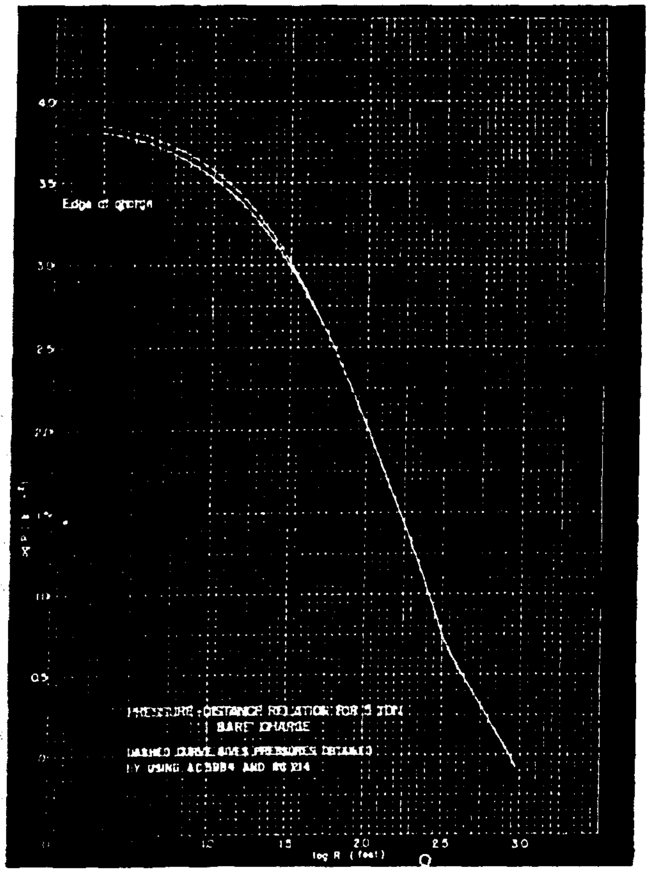
The Terminal Ballistics Branch defined the major fields of its investigation as consisting of investigations of blast, fragmentation, and penetration. Appreciable progress in the study of blast and fragmentation was made during the war, and much was also done to determine the penetration and perforation capabilities of the different types of shot. The work accomplished during the war laid excellent foundations for continued rapid progress in all these fields of terminal ballistics after the war had ended.

Blast Measurements. Until 1943 the scientists at BRL were unable to measure the blast caused by the detonation of high explosives because no gauges adequate for such work had been found. A number of different types, including the piezoelectric gauge, were used, but none was able to furnish data that correlated sufficiently with the effectiveness of bombs as determined by other means. It was not until the piezoelectric gauge had been modified for blast-measurement work in early 1943 that real progress in the study of blast phenomena could be made. This successful development of the piezoelectric gauge for a new use was most fortunate, for HE shell and bombs were used more and more extensively as the war progressed and it was imperative that knowledge of shock-wave phenomena be increased in both scope and depth.

The first investigations conducted with the improved piezoelectric gauge indicated that general investigations of shock waves, whether produced by detonation of high explosives or by the supersonic speed of a high-velocity projectile, would be necessary. Most of what was done was theoretical, with interest focused on such problems as the rise and fall of pressure in front of and behind shock waves. Without the successful completion of the theoretical investigations, many of the recommendations subsequently submitted by the Terminal Ballistics Branch would have been tenuous.

Blast measurements made by use of piezoelectric gauges provided data most useful in determining the destructive capabilities of various shell and bombs. Such points were investigated as the extent to which the force of a blast wave decreases with distance from the point of detonation. In 1943-1944 eighteen major firing programs, involving the detonation of 500- to 10,000-lb bombs filled with different types of high explosive and 5- to 10-lb bare charges of TNT, were conducted for these purposes. In addition to comparative data on the destructive power of different high explosives and the effectiveness of various booster systems, these tests provided a great deal of information about the basic characteristics of blast waves. One outstanding practical result was the adoption of tritonal as a standard explosive for GP bombs.

As part of the general blast program, the effectiveness of plastic explosives in the demolition of concrete structures was also investigated. Several new types of this kind of explosive were developed in an effort to find one that would be superior to blasting gelatine. The relation between the thickness of concrete to be demolished and the amount and shape of the explosive charge to be used was studied, and the behavior of a cased plastic explosive on impact on a concrete wall was also investigated. High-speed photography again proved its usefulness in these studies, providing valuable information on such questions as optimum fuze times.



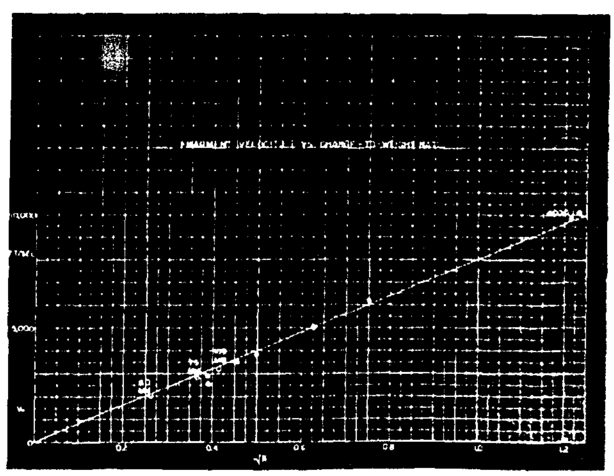
Blast measurement (pressure vs. distance) graph

Fragmentation. For many years before 1940 the fragmentation of HE projectiles had been studied at BRL by means of pit and panel tests, which yielded information as to the number, sizes, and distribution of fragments to be expected from each type of shell. However, very little had been done in the study of what can be termed the ballistic characteristics of fragments, such as velocity, drag, and presented area; moreover, still less had been done in any respect with bomb fragments. As a result, the experimental basis had not yet been laid for formulating laws governing fragmentation or, for that matter, for developing precise methods of evaluating the effects of fragments.

Accordingly, during World War II, the terminal ballistics group at BRL turned its attention to these aspects of fragmentation. In addition, they conducted special tests to determine the fragmentation characteristics of experimental projectiles and bombs and of standard projectiles and bombs with experimental loadings.

To determine the velocity of fragments emitted by bombs and shell, high-speed motion pictures were used at first but were soon abandoned in favor of a more precise electrical system. The bomb or shell to be detonated statically was wrapped with a wire which, when broken at the moment of detonation, recorded the exact time the casing was fractured. At a suitable distance from the point of detonation a screen, through which an electrical current flowed, was fixed; when the screen was cut by the first fragment that reached it, the current was interrupted and the time at which this took place was recorded. The difference between the two times, together with the distance of the screen from the bomb or shell detonated, yielded the velocity of the fastest-moving fragment hurled in the screen's direction. Velocities recorded by such means ranged from 3,500 fps for shell to more than 8,000 fps for large bombs.

The retardation of fragments by air was also studied, to determine the extent to which the initial velocity of a fragment was reduced as the result of air resistance. The needed data were obtained by firing controlled fragments from a caliber .50 smoothbore machine gun past spark-photography stations, and from them a drag coefficient for use in the drag equation was obtained for the fragment tested. This technique could be used, however, only for low-velocity fragments. Drag coefficients for high-velocity fragments, as emitted by the detonation of a 4,000-lb bomb, could be only roughly calculated by reference to high-speed motion pictures taken of them.



Fragment velocity vs. distance graph

A considerable amount of theoretical work was also done on different kinds of targets. Criteria were established for the effectiveness of fragment damage: A fragment capable of perforating 0.125 inch of mild steel was considered effective against aircraft on the ground, but to be effective against aircraft in the air, its perforation capability would have to be increased to as much as 0.375 inch of mild steel. In the same way, with at least 58 foot-pounds of energy, a fragment hitting a man would be considered as having produced a casualty.

Other experiments were conducted to determine the lowest altitude from which bombs could be dropped without the aircraft running the risk of damage by fragments, the probability that fragments from a given type of antiaircraft shell would damage an aircraft, and the height at which an HE shell should be detonated to assure maximum fragment damage to personnel on the ground. In general, these and other similar investigations marked the beginning of the systematic *vulnerability* studies which in the postwar period became an important part of continuing work in weapons analysis.

Beginning in 1943, high-speed X-ray photography was employed successfully in many investigations of the phenomena related to the detonation of high explosives. The special equipment for such work was very much needed, for the detonation of HE charges is accompanied by dense clouds of gas and intense flashes of light which make ordinary photography impossible. The gas cloud could be penetrated by X-rays and so long as the X-ray film was protected by a sufficiently opaque envelope and the equipment as a whole was shielded from blast, very useful pictures could be obtained. By these means a new window was opened to the phenomena of explosion, including the fragmenting of shell and bomb cases. One of the first applications of this technique was in the study of the new shaped charge high explosive antitank (HEAT) shell. The information about the new weapon gained at BRL proved sufficient for the formulation of an acceptable mathematical theory of the shaped charge principle by ballisticians at Aberdeen and in England.

Penetration of Targets. Throughout the war the terminal ballistics group at BRL conducted basic research to obtain data for formulating the fundamental laws of the penetration of targets by missiles and refining the laws of ricochet.

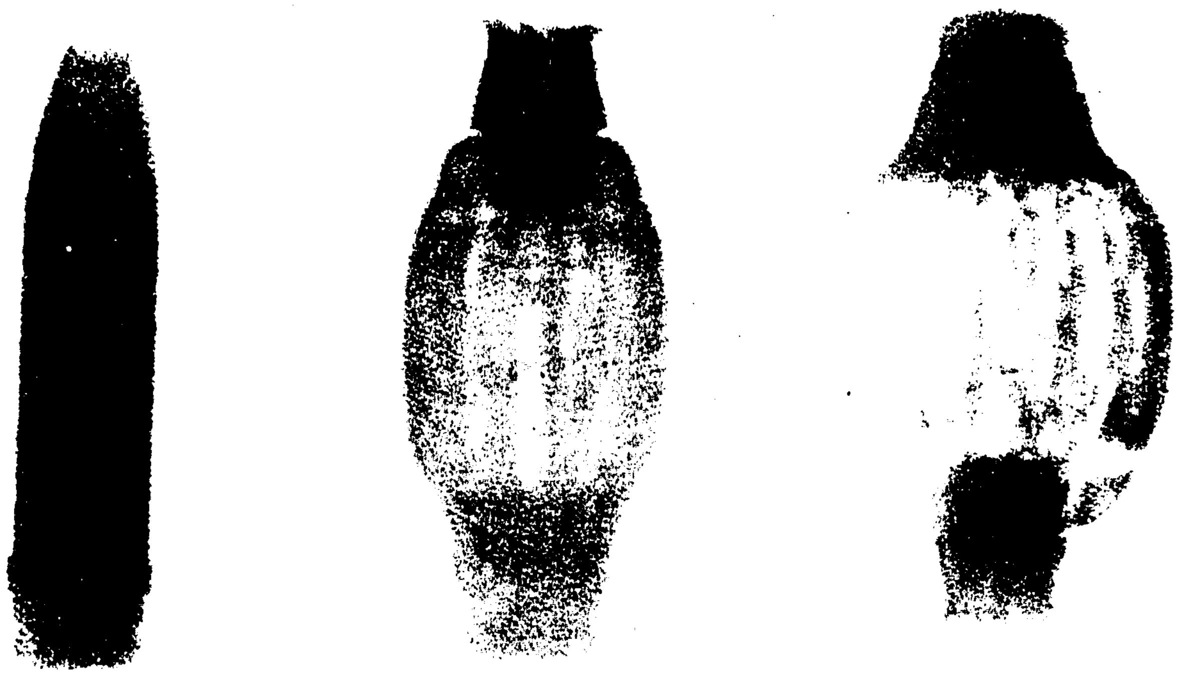
In the first of these two fields of investigation, one line of inquiry sought to determine the capability of steel spheres, cylinders, and fragments of irregular shape to penetrate different media. Missiles of these three types were fired from caliber .30 and caliber .50 smoothbore guns into wood, plywood, and cardboard; the depths to which they penetrated were carefully recorded, and from the data penetration formulas were developed. These formulas were then tested by statically detonating 40-mm HE shell in front of cardboard packs and HE bombs in front of steel plate. The formulas obtained related depth of penetration to the medium penetrated, the striking velocity of the missile, and the distance between the firing point (or point of detonation) and the target.

As progress in the investigation was made, specific problems were posed and answered experimentally. For example, steel spheres were fired against steel pipe in an endeavor to determine the fragment velocities required to silence enemy guns by damage to their recoil mechanisms.

In order to refine the laws of ricochet that had already been established, many different types of firing were carried out to obtain data on the fundamental variables involved: namely, striking angle, striking velocity, shape and density of the missile, and the physical characteristics of the target material off which ricochet occurs.

In addition to the basic work, specific projectiles, both developmental and standard, were fired against specific targets to obtain information about their capabilities of penetrating different media. The use of tipping screens to reduce penetration by causing a projectile to yaw and possibly shatter on impact with armor was also investigated. Attacking the problem of penetration from the other end, the effect of increased spin on the penetrating capabilities of the projectiles was explored.

The special case of the penetration and destruction of concrete, stone, and other masonry structures was also investigated; in this work BRL



0 microseconds *11 microseconds* *20 microseconds*

34 microseconds *42 microseconds*

Flash radiographic studies of 20mm HE shell, statically detonated.

92 microseconds

cooperated with other agencies of the Ordnance Department and with the Corps of Engineers. Bombs with light, medium, and heavy cases and filled with either sand or explosives were dropped on test slabs of concrete and concrete shelters of different thicknesses, and projectiles of various types were fired against vertical slabs and the walls of such structures. These tests showed the velocities required to obtain different depths of penetration, the extent to which the cases of bombs and projectiles were deformed or ruptured, and the extent of damage done by detonation of a missile at different depths of penetration. It was learned, for example, that AP shot and heavy-case bombs were not deformed during their penetration of concrete, but that HE shell and light-case bombs were likely to collapse on impact if their striking velocity was high. Information essential to the proper timing of fuzes for concrete-piercing shell and bombs was obtained, and this was promptly made available for combat use. The conditions under which the different types of missile available could be most advantageously employed against concrete and stone fortifications were determined and this information was made available to the Forces in the field.

Finally, attention was given to the problem of cratering enemy airfields, with special emphasis on delay-fuzing of the bombs and projectiles to be used for that purpose. From the data obtained in a large number of tests, the relations among the size of craters produced, the weight of the charge employed, and the depth at which the charge was detonated could be determined.

During the war, the research function of the Ballistic Research Laboratory had to give way in part to the solution of more immediate problems. The Forces in the field needed technical information and assistance in solving many practical problems to which the Laboratory held the key. The Army Air Corps, for example, needed advice in devising a bomb pattern that would assure a high probability of hitting a bridge on a single bombing run; the Field Artillery needed shell with a special fuze that would not function when it hit treetops in the Pacific jungles but would be reliable and instantaneous on hitting the ground; and both the Army and the Navy needed new ballistic tables to help guarantee that the concrete pillboxes guarding the shores of German-held Europe would be destroyed before our infantry reached them.

Such problems took time away from basic research, but most of it was of such character that only a well-organized and experienced ballistic research installation could do it. The last section on the record of BRL in World War II will show how these problems of applied research were handled during the war and, in doing so, will indicate something of the magnitude of the Laboratory's contributions to victory over Germany and Japan.

TECHNICAL INFORMATION FOR THE ARMED FORCES

The provision of technical information and special technical assistance to the combat troops in the field, responsibility for which was accepted by BRL from the beginning of the war, required more and more attention as the war progressed. By early 1944 this special work had grown to such proportions that two new branches — the Field Facilities and the Special Problems branches — were created to handle the many problems it involved. Together, these branches had four principal functions. They answered the many specific requests for information that BRL received from the field; published reports and summaries of reports on the practical problems of bombing and the effectiveness of fire of all kinds; published data needed for the efficient use of various weapons, especially guns, mortars, and their ammunition, rockets, and bombs; and trained and equipped teams to calibrate guns in the field. At practically every step of their work the Field Facilities and Special Problems branches drew on the resources and experience of BRL's entire organization.

Publication of Ballistic Data. As early as 1937 Colonel Zornig had concluded that many advantages could be gained by publishing all available ballistic data on ammunition, cannon, and other Ordnance weapons in a single handbook for use by Ordnance engineers. It was not until 1941, however, that a project to this end could be put under way; it called for the preparation of an engineering handbook on standard projectiles to incorporate all the information on their physical characteristics, ballistics, and effectiveness. The principal sources of information were to be the reports, drawings, and firing tables at BRL. Issued in incomplete form in 1944 as the *Ballistic Research Laboratory Handbook of Ordnance Engineering Data,* it proved so useful that at the end of the war it was being revised and updated for reissue and wider distribution.

Another of BRL's contributions to the technical literature published by the Ordnance Department during the war was the material it submitted for inclusion in the three volumes entitled *Terminal Ballistic Data,* the first two volumes of which were issued in August 1944, the last, in September 1945. Dealing for the most part with the means of defeating concrete fortifications and armored vehicles, this material was first intended for use in defeating the Germans. It included graphs for each gun, ammunition, charge, and range combination indicating the number of rounds to be fired to give a 90 percent probability of perforating various defensive materials of different thicknesses. It contained calculations of what would be required to breach concrete walls as massive as 10 feet high and 10 feet thick; the principal exterior ballistic characteristics of most projectiles; data on the cratering capabilities of many HE shell; and diagrams indicating the area within which personnel would probably be incapacitated by the detonation of different calibers of HE shell.

Another section presented comparable data for use in defeating the earth and log fortifications of the Japanese in the Pacific. A third section

presented similar data on bombs and bombing techniques; it included graphs showing the effects on the trajectories of different bombs of such factors as the altitude and speed of a bomber at the moment of bomb release and variations in air density.

In 1948 these three volumes were republished as TM 9-1907, *Ballistic Data, Performance of Ammunition,* which was still in use at the end of 1956.

Field Artillery Problems. One of the major problems undertaken by the Special Problems Branch was the provision of specific information about time fuzes for use by gunners in the field. A great many facts had to be collected about such factors as desired point of burst under standard conditions, the conditions that affect the functioning of the different types of time fuzes, and optimum fuze settings to meet various combinations of conditions. Firings of projectiles with different fuzes were conducted at Aberdeen and the data obtained were used to develop formulas for determining fuze settings for a wide variety of combat situations; these formulas were used to compute recommended fuze settings for inclusion in the firing tables for different gun-ammunition combinations.

After this work was done, analysis was carried further to obtain specific information on such problems as the number of HE shell required to obtain a given effect within a given target area (for example, within an area of 100 yards by 100 yards), when detonation was at the optimum height above the ground. This particular study was extended to all artillery weapons, and the information obtained was prepared for easy use by artillerymen in the field.

As an example of other special problems worked out in this area, a study was made of the German 88-mm gun to determine its parts that were most vulnerable to fragmenting shell. On the basis of the findings of this study, computations were made of the number of rounds required to destroy 50 percent of the enemy guns in given areas.

The Laboratory was also requested to provide technical information for use in training personnel at the Field Artillery School at Fort Sill. This covered a wide range of subjects and required much research. It included information on the use of field chronographs in the calibration of guns, the composition of ammunition lots, dispersion and its causes, the heating of guns and its effects, and the effects of the exterior finish of shells on their range.

Ballistic and Technical Service Teams. As part of its work to assist artillerymen in every way possible, BRL trained Ballistic and Technical Service Teams to go into the field and calibrate guns. Calibration had been done at Aberdeen for many years, but it was not until the war that an attempt was made to provide trained men and equipment to measure the muzzle velocities of individual guns in the field and thereby aid in increasing the accuracy of their fire.

The first teams of this type were trained at BRL in the fall of 1942, equipped with the T2 field chronograph and other devices and sent out to work with antiaircraft artillery units in this country.

In the following spring, equipment which was the basis for the development of the T6 field chronograph was procured from the Canadian National Research Council. It was used for the Antiaircraft Command and then sent with the first Simon Mission to Great Britain for use in grading 105-mm ammunition to be used in the Normandy invasion.

In April 1944, (by this time the T6 field chronograph was available), six teams were organized for the calibration of artillery pieces; their training at Aberdeen consisted of a 12-week course in electronics, ballistics, and the operation of the T6 field chronograph, photoelectric cells, and counters they were to use in the field. Before the first class had graduated, reports from the field indicated that additional personnel and more teams were needed; accordingly, the strength of each team was increased from one officer and five enlisted men to two officers and eleven enlisted men, and the number of the teams was increased from six to fifteen. Upon completion of the course at Aberdeen, the teams were sent to Fort Bragg for two weeks of additional training and then shipped out to different stations in this country and overseas.

Pattern Bombing. It was a relatively short step from calculating the number of artillery rounds needed to destroy a ground target to assisting the Army Air Corps in designing bombing patterns that would increase the probability of destroying a target from the air. The need for such patterns arose from the fact that against certain types of targets, such as bridges, which could be destroyed by one hit, the objective of a bombing mission was to get that hit, not to saturate the area around the target with bombs. BRL's work on this problem contributed much to its practical solution.

From bomb patterns BRL turned to patterns for the distribution of antiaircraft shell to assure a high probability of getting at least one hit on an enemy aircraft. From there it went on, again at the request of the Army Air Corps, to assist in working out aiming procedures for laying parachute mines across the entrances of typical enemy harbors. Estimates were made of the probability that a ship could survive passage through a field of mines distributed at random and of the spacing of mines to obtain optimum results in channels of given widths.

FIRING AND BOMBING TABLES

Both firing and bombing tables were kept up to date throughout the war, with the greatest amount of new work concerning bombing tables and firing aids for aircraft weapons.

Preparation of Tables. The wartime workload was extremely heavy, additional tables had to be prepared for all new gun-ammunition combinations and for the new rounds of ammunition fired in standard guns. In addition, firing tables had to be prepared for the ground-fired rockets that came into general use during the last years of the war; a considerable amount of basic work had to be done at first, but it was done as quickly as possible and thereafter the production of tables for rockets was relatively routine. In all this work the differential analyzer was used to compute tables directly from firing data, so that ballistic tables did not have to be used. Had it not been for this, the Computing Branch would have required a staff several times as large as the one it had when full wartime strength was reached in early 1945.

In the preparation of bombing tables certain problems arose that were not encountered in the work on artillery firing tables. This was because the altitude limit used for bombing tables until 1940 had been 20,000 feet and the tables themselves had been based on data obtained by test drops from altitudes up to 18,000 feet. In 1940 the Army Air Corps raised the altitude limit for bombing tables to 35,000 feet and called for the tests to obtain the new data to be conducted at 25,000 feet. In 1942 the Army Air Corps requested bombing tables for altitudes between 50,000 and 60,000 feet, but the data for these were to be extrapolated from the data obtained by the test drops from 25,000 feet; this reduced somewhat the task of preparing the new tables, but the results were not very accurate. Gradually the altitudes for regular range bombing programs were standardized at 2,000, 10,000, 25,000, and 35,000 feet; then test bombs were dropped from each altitude to get the data needed, using a single air speed for each altitude. The tests from the lower altitudes were conducted at Aberdeen Proving Ground; those from the higher altitudes were run at Lake Muroc, California. Between 1940 and 1944, 2,500 bombs were dropped at Aberdeen for these purposes, and during the last half of 1944 the Aberdeen Bombing Mission at Lake Muroc dropped 600 more. These tests provided data for the preparation of 220 bombing tables for bombs of different types and weights.

The increasing use of machine guns as aircraft armament and the adoption of 20-mm guns for this purpose created several major problems for the group assigned responsibility for the preparation of firing tables for these weapons. Standard firing tables were relatively useless, for an aircraft gunner in combat normally had no time for anything more than the operation of his weapon; duels between aircraft moving at high speed and changing position relative to each other did not provide opportunity for careful calculation of firing data and the adjustment of sights. Secondly, the forces affecting the fire of bullets fired from a moving aircraft were radically different and much more complex than those encountered on the ground.

The aiming system taught to aerial gunners in the Army and Navy up to 1943 had left something to be desired. The heavy losses of the Eighth Air

Force to enemy fighters on each of its early bombing missions over Germany directed the attention of the Services to the need for better training procedures in this field and for the development of usable firing aids. It was recognized that the problem of firing at a rapidly moving target from an aircraft which was also moving rapidly was complex in itself, and that it was further complicated by the speed at which the prediction-aiming-firing sequence had to be completed; nevertheless, accuracy of fire was indispensable and had to be attained.

In 1943 this problem was the subject of a conference at Fort Myers, Florida, which was attended by a representative of BRL. Certain decisions were made there and, in the months that followed, BRL's mathematicians worked out a number of formulas and very simple tables which could be memorized and quickly applied by aerial gunners. Adoption of these devices aided in improving the training of these men and assisted in attaining greater accuracy of aircraft gun fire.

Dispersion of Aircraft Gun Fire. In the general investigation of the problems of aircraft gunnery it was found that, in addition to inadequacies in the training of gunners, certain other deficiencies existed. These included errors inherent in the sights and excessive dispersion of fire.

BRL's chief responsibility in correcting this situation was to reduce dispersion. To obtain the information for working on this problem, the two caliber .50 machine guns in a ball turret of a B-24 were fired together when the aircraft was flying at altitudes between 1,300 and 5,000 feet and at true air speeds of from 140 to 220 mph; each burst consisted of twenty rounds and the ranges at which dispersion was checked were between 600 and 1,600 yards. Three directions of fire were employed: 45 degrees forward, 45 degrees to the side, and straight down. The trajectories of the bullets of each burst were recorded by a ballistic camera and motion picture cameras. In order to check the recorded dispersion patterns, the two guns were also fired when the aircraft was on the ground. Still other firings were made from machine guns installed in four different types of pursuit planes.

From these tests it was concluded that the principal factors responsible for excessive dispersion of fire were variation in ammunition and, to a lesser extent, variation in guns. BRL recommended that attempts be made to obtain rounds with uniform ballistic coefficients and that closer surveillance be maintained of aircraft machine gun ammunition. The Special Problems Branch was given the task of surveillance. The staff conducted regular tests of samples submitted by all manufacturers producing ammunition for aircraft guns.

In addition to this work on dispersion, BRL computed the initial conditions required for hundreds of pursuit curves needed to design computing gunsights for aircraft.

ORDNANCE ENGINEERING

As more new weapons were put into development by the Technical Division, OCO, and the demand for their delivery to the field became more urgent as the war progressed, BRL was called upon to provide essential basic engineering data for use in eliminating difficulties encountered in the design work. These *trouble-shooting* assignments were given high priorities, in order that design work might continue while design problems were being solved. Many of these assignments were handled by the Ordnance Engineering Branch of the Laboratory, and the Branch worked in close cooperation with the Proof Division of the Proving Ground and with other branches of BRL.

Ballistic Design. A large part of the Laboratory's participation in wartime design work consisted of the calculation of interior ballistics data for guns expected to give a certain performance under specified conditions. However, because it was a policy to utilize as many existing components as possible in new weapons and to rely on established designs and methods of manufacture wherever possible, problems of adapting the new to the old were constantly arising and BRL was called upon to contribute to their solution. As experience in this field accumulated, the Laboratory began to analyze the specific design problems that had already been dealt with in an effort to arrive at general design suggestions for new weapons.

The Laboratory made several significant contributions to the development of tank guns. In 1941, when it was recognized that the performance of the M2 75-mm gun for the M3 medium tank would have to be improved, BRL studied the existing model's muzzle velocity in relation to its powder charge and recommended that the length of the tube be increased. Later, on the strength of its various ballistic investigations, BRL recommended that a caliber of approximately 3 inches be considered as best for tank guns; moreover, it contributed several suggestions for modifying the design of tank guns to achieve maximum effect. Again, the Laboratory emphasized the need for closer attention to improving metallurgy as a means of improving gun design. This recommendation was the direct result of the explosion of two guns in proof firings and BRL's analysis of the causes.

In 1943 the development of new mortars and ammunition became a pressing matter as the value of these weapons in jungle warfare was recognized. BRL became involved in the design work and made useful contributions in the form of essential ballistic data and suggestions for obtaining uniform muzzle velocities and projectile stability. As a result, new 60-mm, 81-mm, 105-mm, and 155-mm mortars and such special weapons as the spigot mortar and the cannon grenade were designed.

The strain measurements and analyses of gun tubes, chambers, breech rings, mounts, carriages, and trails were of value in checking safety factors, determining the relative importance of band and powder measures, and designing guns of minimum weight by utilizing a higher but more uniform stress distribution.

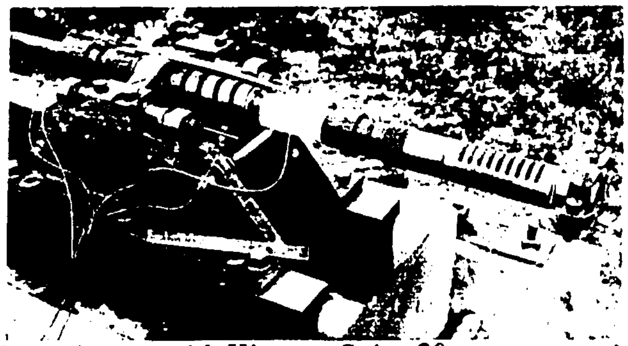
Recoil Systems. In the early part of 1939 it became evident that the recoil data furnished by the majority of the gun manufacturers were unreliable. Accordingly, in August 1939 OCO requested that BRL determine experimentally the trunnion reactions of aircraft machine guns. Piezoelectric gauges were used, and the first test was run in April 1940.

Although the original purpose of this work was to furnish data for use in designing mounts, it was found as tests continued that the records of horizontal force versus time and displacement versus time provided a basis for evaluating the performance of a gun and its components. In the process of making these tests a method was developed for the dynamic analysis of recoil systems, which was applied to aircraft, tank, and antitank guns and to mortars. It was used to determine, for example, the effects of various recoil-absorbing devices for caliber .30, caliber .50, and 20-mm aircraft guns, to evaluate changes in the buffers and recoil systems of 37-mm guns, to determine the performance of special recoil fluids at extreme temperatures, and to find the results of various changes in the components of different automatic weapons. It was concluded, among other things, that for optimum recoil conditions it was desirable to have a continuous rise in pressure until a projectile left the tube and, thereafter, an approximately constant pressure until the end of the recoil stroke.

In each instance of the dynamic analysis of recoil systems, the magnitude of recoil pressure was determined, the performance of the recoil system was evaluated, and corrective action was recommended when needed. As an example of the practical results obtained from this work, action was successfully taken to reduce the weakening and breakage of springs which had been quite prevalent in development-type weapons; in turn, this contributed directly to the development of light-weight rapid-fire guns with high-velocity recoil.

Analysis of Gun Mechanisms. BRL made detailed analyses of the mechanisms of certain automatic weapons while they were still in development. A fairly uniform procedure was followed in this work; a model was analyzed and tested, the types of failure were noted, recommendations to eliminate the causes of failure were submitted to the developing agency, the necessary modifications were made by the developing agency, and the modified model was tested. The pattern was continued until a reasonably satisfactory product was obtained.

A good example of the Laboratory's practical contributions in this field is found in its work on the development of the American version of the Hispano-Suiza 20-mm automatic aircraft gun. In 1939 the United States procured several of these cannon from the French Government and, after



Experiments with Hispano-Suiza 20mm automatic aircraft gun.

several short tests, adopted the gun for use by the Air Corps. Before the cannon could be produced in this country, the Germans overran France. Manufacturing plans therefore had to be prepared from measurements of the actual guns in our possession and data furnished by the British and certain French groups. However, when the American versions were finally produced and subjected to endurance tests of 5,000 rounds, defects were noted. Components of the bolt tended to break, the driving and extractor springs proved to be weak and easily broken, the gun tended to misfire as soon as it became warm, and excessive force was noted at the trunnions. BRL studied these problems, made suggestions to correct them, and tested the modifications it had recommended. The gun was finally brought to a level of development at which it functioned satisfactorily on rigid mounts, but, when installed on less rigid mounts in aircraft, it displayed new weaknesses.

The British solved this problem by using heavier mounting fixtures. BRL, however, designed a new lightweight version of the gun for turret mounting. The barrel length was materially reduced, the sear mechanism was redesigned to reduce the effects of acceleration, and the principle of the electric bolt was revived. Similar innovations were recommended for the design of ammunition for this gun. The result was an excellent 20-mm cannon for aircraft use.

SURVEILLANCE OF AMMUNITION

One of the most successful applications of ballistic research made by BRL during the war was the development of statistical procedures for the quality control of ammunition, conducted under the leadership of Colonel Simon. The product of this work was a highly specialized tool of great value, useful in guaranteeing that ammunition would meet all operational requirements, in obtaining acceptable ammunition as economically as possible and maintaining effective surveillance of it after it was stockpiled.

The procedures for quality control consisted essentially of systematically selecting samples at different stages of production, inspecting these for the characteristics to be considered at each stage, noting the average value and the spread between the highest and the lowest values for each characteristic, and approving or rejecting the lot on the basis of these findings.

The chief value of this procedure during production was its prompt and accurate detection of sources of trouble, which therupon could be economically eliminated. In addition, it provided a guarantee that the accepted items would meet all the requirements specified for military use. Finally, it offered considerable opportunities for improving the Ordnance Department's procedures of acceptance inspection and provided an excellent basis for grading the stores of ammunition stockpiled in the Communication Zones of the several theaters of operation.

The Sampling Technique. A reliable sampling technique to determine the acceptability of ammunition was essential to the efficient operation of the ammunition industry as a most important element of wartime production. The quantities of ammunition required were enormous, so that neither time, manpower nor money could be wasted by inefficient production methods or by waiting until production had been completed before taking the first step to determine whether the product would be acceptable for field use. .

This did not make final inspection unnecessary, however. The application of quality control during production was largely by the manufacturers themselves, who used mathematical data and other information provided by BRL. By mid-1940, BRL had developed the first standard sampling inspection plans and acceptable criteria in the Department of Defense (Military Standard 105A). Nevertheless, each lot of ammunition produced had to be

inspected for acceptance by the Ordnance Department and again the sampling procedure operated most satisfactorily. By using sound statistical procedure, sampling was placed on a reliable basis. The samples were tested either at Aberdeen Proving Ground or one of the arsenals. The inspection was conducted under the supervision of the Industrial Division, OCO, but BRL reviewed the reports of all the tests as a means of increasing the effectiveness of the statistical procedure employed.

Surveillance of Ammunition in the Field. Quality control was needed not only during the production of ammunition and its acceptance but also in the surveillance of the large quantities of ammunition that were stockpiled in the ZI (Zone of Interior, the continental Unites States) or overseas. Early in the war Ordnance noticed distinct variations in the range of 105-mm ammunition, variations first explained by differences in the fit of the rotating bands. However, investigation quickly revealed that variations in the surfaces of ammunition produced by different manufacturers also affected range.

BRL was assigned to correct this situation, and its work constituted one of the major wartime successes of its Surveillance Branch. Because the 105-mm ammunition already stockpiled in Great Britain for use in the invasion of the Continent had to be of superior accuracy — success in the invasion was essential to the defeat of Germany — in early spring 1944 Colonel Simon and a small group from the Laboratory went to England to classify this ammunition into grades according to ballistic performance. The classification procedure adopted called for systematic sampling of ammunition lots, test-firing the samples, and analyzing the test data to determine ballistic characteristics. Five rounds were taken at random from each lot for test-firing to determine projectile performance; five more rounds were also taken at random, projectiles of known ballistic performance were substituted for the one they contained, and the modified rounds were fired to determine the performance of the propellant. Only 2,500 rounds had to be fired to classify the stock of 837,000 rounds. A 0.3 percent sample was sufficient for grading the entire stock.

The data yielded by the test-firings, when analyzed, furnished information about the effects of propellant, rotating band, and surface finish of projectile on the range obtained. On the basis of range only, the stock of 105-mm ammunition was graded as follows:

14% — range comparable to that required by the firing tables
31% — range tended to be long
41% — range tended to be short
14% — range sufficiently varied that lot should be used for area fire only

With the grading of 105-mm ammunition in Great Britain completed, Colonel Simon and his group from BRL went to the North African Theater of Operations. Most of the old stocks of 105-mm ammunition in that theater had already been expended but reports from Italy indicated that another problem had reduced the accuracy of artillery fire. It was well known that the ballistic characteristics of a gun, as determined by bore erosion, wear of the forcing cone, and such factors, affect its velocity, range, and accuracy. It was also recognized, however, that the individual adjustment of each gun in a battery for accurate battery fire on a target was extremely time-consuming and frequently dangerous in combat. Accordingly, the Simon group endeavored to educate artillery units in the factors that affect accuracy of fire and trained a team to calibrate guns in the field and to assist in determining when worn tubes should be replaced.

The group then returned to Great Britain and trained another calibration team for service on the Continent. The war in Germany was drawing to a close, so the group assisted the Chief Ordnance Officer of the European Theater in selecting the ammunition lots to be sent to other theaters after V-E Day, those to be renovated, and those to be scrapped.

Throughout the history of our country, victory in a major war has been followed by disarmament and the channeling of the nation's energy to bring about a quick recovery from the stresses and strains of wartime economy. Had the period following V-J Day run true to this pattern, the Ballistic Research Laboratories would have promptly reduced expenditures, discharged many personnel, and concentrated on only the most critical of the problems of contemporary ballistics. The pattern was broken, however; in place of the international amity that had been hoped for when the United Nations Organization was established at the San Francisco Conference, tensions developed among the nations. Instead of disarming, the Great Powers were rapidly increasing their military budgets to meet the new threat to peace and security. Moreover, as scientists and engineers developed new arms for use against aggressors, the frontiers of science and technology were expanded at breath-taking rates. New weapons became obsolete before field troops could be fully trained in their use.

One of the great advances made by military technology in the decade following the Japanese surrender was an enormous increase in the speed of combat aircraft. The 300-mph rate that had been considered excellent for the best planes of World War II gave way to 600 mph in 1954, and in 1955 a speed of 700 mph was recommended as one of the design requirements for new experimental aircraft. In less than a decade the operating speed of combat aircraft had been more than doubled; a trip of 5,000 miles, which would have required more than a day of uninterrupted flying by a B-17, could be made in about nine hours by a B-47.

Fire power was another area of military technology in which the postwar decade produced revolutionary changes at an ever-accelerating rate. TNT, which was twice as powerful as gunpowder, had been the basic explosive of the two World Wars, but it was reduced to a low level of comparative effectiveness by the research conducted so successfully in nuclear physics and its applications. To describe graphically the increase of destructive power, the high-explosive load of a heavy bomber of World War II could be represented by a 4-inch stack of one-inch cubes; on this scale, a stack of cubes 66 inches high would represent the destructive power of the bomb dropped on Nagasaki, and a stack 63 miles high would be the equivalent of the thermonuclear bomb. This bomb has substantially more destructive power than was delivered by all the combatant forces on all the battlefields of World War II.

NEW FRONTIERS OF BALLISTIC RESEARCH

The solution of problems encountered in the development of shell, rockets, and guided missiles depended heavily on mathematics, practically all of the physical sciences, and the progress achieved by applied science and technology. The general development of electronics, the growth of weapon systems analysis, and the progress made in nuclear research in the nation as a whole characterize the accomplishments from 1946 to 1956.

The Impact of Electronics. Perhaps the most significant progress in military technology made after V-J Day was the result of the postwar revolution in electronics, which was applied to improved ranging and detection devices, fuzing systems, fire control, and a wide variety of other military uses.

BRL developed electronics devices with a sensitivity to signals as weak as 10^{-14} watt. Instruments equipped with such devices were capable of performing extremely delicate operations in very short periods of time. In addition to extreme sensitivity, these devices had far greater precision than any of the earlier instruments. This was most fortunate, for precision became increasingly necessary as more searching analyses were required and as the number of phenomena to be analyzed increased. In addition, the resistors, capacitors, transistors, and other electronic devices, once they were designed and tested, could easily be manufactured for use in the most demanding equipment.

The Analysis of Weapon Systems. As the science of ballistics was applied to the design and measurements of each new type of ordnance weapon, and as the variety of weapon types rapidly increased, the attention of ballisticians was necessarily directed to the various weapons combinations that could be

used in different tactical situations. This new field of inquiry called for detailed information about all aspects of each anticipated type of combat situation, including the general types of weapon that each side could bring into action and all the principal performance characteristics of each weapon under all the special conditions in which it could be effectively employed. Such problems were enormously complicated by the rapidity at which new and potentially more effective weapons were being developed. Also, the development of thermonuclear bombs and warheads, together with the production of extremely long-range bombers and guided missiles, radically changed the strategic basis of warfare by increasing the probability that a combatant nation would lose much of its materiel and industrial potential within a short time after a war began.

Working within this frame of reference, the ballisticians at BRL applied theoretical mathematics, statistics and probability theory to operations research in order to determine the effectiveness of individual weapons and combinations of weapons in given combat situations. The ultimate purposes of such weapon and weapon system analysis were to select the weapons and weapon system that promised to be the most effective for a given use, and to select combinations of weapons by which a given combat situation could be handled most satisfactorily. Various weapon systems, reduced to performance data, were taken through a series of combat situations in computing machines, chance factors were injected, and the performance computed. High-speed computers made it possible for this procedure to be repeated several thousand times, if necessary, so that probabilities could be definitely established. Not only did this method determine the probable outcome of engagements, which other otherwise could not be found except by large-scale maneuvers or actual combat; it also enabled ballisticians to recommend the types of weapon that should be developed to maximize the proabaility of victory.

The Implications of Atomic Warfare. Despite its very rapid growth after 1945, atomic warfare was still so young that none of the experts could foresee the effects it would have on general warfare. The basic question, still unanswered, was whether or not the thermonuclear weapons would render all traditional military equipment and tactical and strategic doctrine obsolete. Military planners gave more attention to new weapons and weapon systems with the greatest combat usefulness in a war in which thermonuclear bombs and warheads would be used.

THE BALLISTIC RESEARCH LABORATORIES

Because of these advancements in weapon systems, BRL's work expanded in scope as the revolution in warfare progressed. Emphasis was placed on adaption to changes in military materiel while basic investigations needed to support the new technology were continued. The trouble-shooting activities that had necessarily taken up so much time during World War II were reduced to a minimum and long-range research was initiated.

Changes in Organization. In August 1945, six branches were raised to laboratory status:

Interior Ballistics Laboratory
Exterior Ballistics Laboratory
Terminal Ballistics Laboratory
Ordnance Engineering Laboratory
Ballistic Measurements Laboratory
Computing Laboratory

Although not fundamentally an organizational change so much as a change in titles, this action nevertheless facilitated both the expansion and the integration of new responsibilities as they were assumed in response to continued technical advances.

At the same time, the Computing and Analyzer Sections that had been maintained at Philadelphia throughout the war were deactivated. The need for them had ended with the defeat of the Japanese.

In 1952 the Surveillance Branch was raised to laboratory status. In February 1954, however, it was redesignated the Surveillance Branch and assigned to the Weapon Systems Laboratory.

The creation of the Weapon Systems Laboratory in January 1953 was the most significant single change in organization made after the end of the

war. This action was taken in recognition of the increasing need for weapon effectiveness and vulnerability studies, which were the new Laboratory's primary responsibility. Before January 1953 this work had been done principally by the Ordnance Engineering Laboratory.

In addition to these major changes, some activities were dropped as the need for them ended, others were added to meet new requirements, and from time to time still others were combined either to facilitate work or to make possible better results. However, none of these minor changes had any significant bearing on the work of the Laboratories as a whole.

Expansion of Physical Facilities. When the enemy finally surrendered, BRL had on hand a list of new construction projects, and the need for each was self-evident.

The first step was the addition of a wing to the main building to house the new computing equipment, some of which was still in development. The ENIAC was moved into this wing when it was completed in 1947. Later in the same year a building to house the flexible-throat supersonic wind tunnel was finished and the new tunnel was put to work. In December 1948 the Terminal Ballistics Laboratory Building, directly behind the main BRL building, was occupied. Then, after a lapse of several years, three other buildings were completed in rapid order: the Surveillance Laboratory Building in August 1953, the Shaped Charge Building in early 1954, and the Interior Ballistics Building in November 1954. A building to house a second supersonic wind tunnel was also constructed.

Each of these new structures was designed to meet the special requirements of the laboratory or laboratories that occupied it. The additional space was indispensable to the efficient performance of BRL's mission, and this expansion was more than justified by the increased productivity of the organization as a whole.

Appropriations for Ballistic Research. In common with the other research and development agencies of the Department of Defense, BRL required and received larger appropriations after the war than were obtained before Pearl Harbor. This reflected the increasing complexities and costs of ballistic research to meet the requirements of the new warfare. From the $1,600,000 budget in fiscal year 1945, BRL's budget was raised to $4,900,000 for fiscal year 1948, and thereafter the annual budget, with the exception of that for fiscal year 1952, leveled off in the neighborhood of $15,000,000. This amount was for research and development expenses only, and did not include for example, the funds expended for permanent construction.

Possibly the most outstanding change in the method of administering research during the postwar years was an increasing dependence on private contractors and other Government agencies for the performance of work essential to BRL's program. As much as 25 percent of the total appropriation for research in the years from 1953 to 1956 was channeled to such groups.

Not all of the money in each annual budget came from Ordnance research and development funds. Because of its need for information about missiles, vulnerability of aircraft to ordnance weapons, and other subjects the Air Force gradually increased its support of BRL activities. In fiscal year 1955 it provided almost 20 percent of all the funds BRL received for research. Comparable services performed for other Ordnance installations, the Navy, the Armed Forces Special Weapons Project, and other Government agencies resulted in appropriations of approximately $1,000,000 a year.

The Recruiting of Scientists. The Laboratory's wartime staff was rapidly reduced as the conflict drew to a close. By September 1945 the number of professional personnel stood at approximately 600 and by the year's end it was 435. However, restaffing was begun almost at once and by the end of June 1946 the number on the rolls was 516. In this rebuilding the most noticeable trend was the replacement of military by civilian personnel in the professional and subprofessional grades, necessary because of the need for a second and a third shift for operating the supersonic wind tunnels. By June 1946 only 22 military staff members were left at the Laboratories, and they were divided almost equally between officers and enlisted men. Approximately 60 percent of the civilian staff were professionals; this indicated the high level of research that was conducted.

Increasing the size of the BRL staff in a period of rising costs and stiff competition for experienced people was not without major difficulties. The demands of industry and other Government agencies for people with the types of training and experience that BRL required compelled the adoption of several enterprising programs to attract the professional people needed to perform high-level work. BRL, with the cooperation of OCO, drew heavily on enlisted personnel who had obtained bachelor's, master's, and doctor's degrees in the various sciences before entering the service; such men were assigned to BRL as technical specialists. Furthermore, as their separation dates approached, vigorous efforts were made to retain them in civilian status so as to fully benefit from their experience in ballistics research.

Another approach to the problem of obtaining young scientists and technicians was initiated in 1947, when the first summer employment program was put into effect. Twelve carefully-selected students majoring in certain fields of science and engineering at nearby universities were given summer jobs and intensive indoctrination in general ballistic research. The results were favorable and the program continued; the number of students increased to fifty the second summer. An appreciable number of scientific and technical personnel were obtained by this method; moreover, because of the screening provided by the program, the quality of young men engaged was uniformly high. The summer employment program remained a part of BRL's system for recruiting personnel.

Because of these new programs, the assistance of the Scientific Advisory Committee was not needed for recruitment as it was between 1940 and 1945. Nevertheless, the Committee made a valuable contribution to BRL's problem of retaining scientific personnel by suggesting the establishment of what became known as the Ballistic Institute.

Within six months after the end of hostilities with Japan, it was proposed that arrangements be made with nearby universities for individual staff members of BRL to complete their graduate work, and that certain special courses be given at BRL for graduate credit. Much had to be done before satisfactory arrangements could be worked out with the universities concerned, and in 1948, D. C. Jackson, Jr. was added to the staff as Chief of Scientific Training to maintain liaison with the participating universities, assist BRL personnel in coordinating their graduate programs with their research work at BRL, and take charge of the Ballistic Institute by which these activities were to be handled.

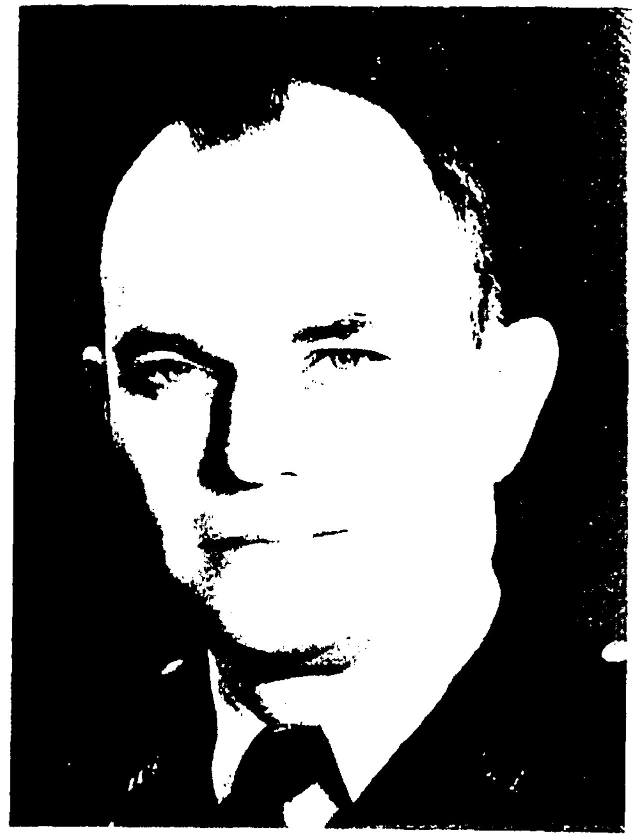
COL Alden B. Taber, Director of BRL 1950 to 1953

For the qualified staff members who wanted to take graduate (and undergraduate) instruction at nearby universities, BRL arranged irregular working hours to permit travel to Washington, Baltimore and College Park in Maryland, Newark, Delaware, and New York City. Some thirty degrees, ranging from bachelor to doctorate, were obtained by these means from 1950 to 1956.

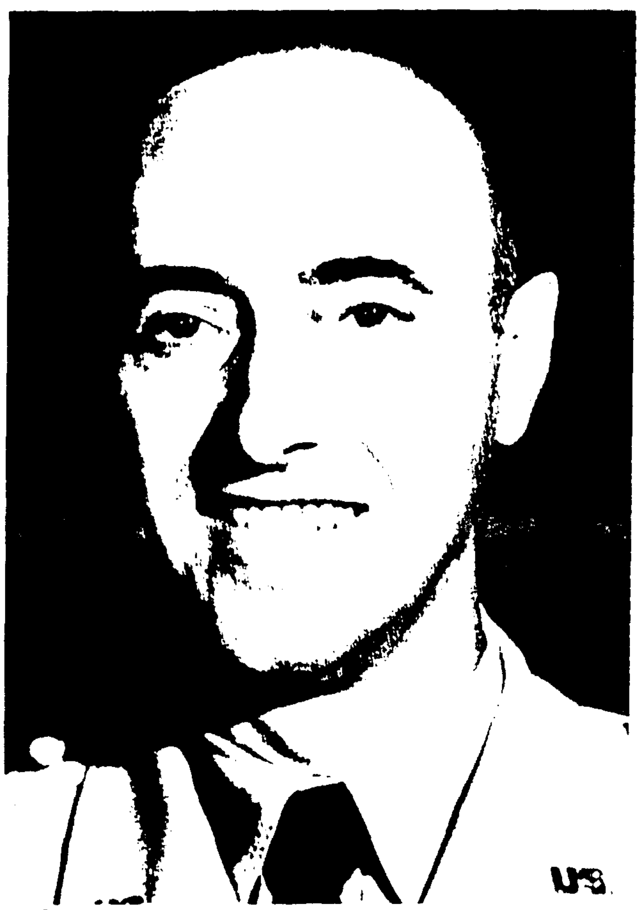
The in-service training program was extremely popular with BRL personnel. Starting with seven

courses and 144 students in 1948-1949, the Institute offered twenty courses to 446 students by 1950-1951 and in 1954-55 registered approximately 750 students. These services were available not only to BRL personnel but also to staff members of the Development & Proof Services, and the Ordnance School at Aberdeen Proving Ground. Among the courses most frequently given were Coding for High-Speed Digital Computers, ORDVAC Coding, Seminars for Coders, Modern Higher Algebra, Vector and Tensor Analysis, Mathematics Seminars, Electronic Analysis, Electricity, Electronic Circuits, and Statistics.

In the early part of the Ballistic Institute program, the scientific staff of BRL provided most of the instructors for these courses, but this took too much time away from their other work and could not be continued. Arrangements were made with the University of Delaware staff to teach all the desired courses, with the exception of a few specialized fields which could be handled only by BRL staff members.



COL Charles L. Register, Director of BRL 1956



COL Angelo R. Del Campo, Director of BRL 1953 to 1956

The results were excellent in all respects. One of the major benefits obtained from the Ballistic Institute's program was the boost in morale of BRL's young scientists who were given the opportunity to continue graduate work for credit.

Leadership. Colonel Simon continued as Director of BRL until the end of 1949, when he became Director of the Ordnance Research & Development Division, OCO. He was succeeded by Colonel Alden B. Taber, 1950-1953, who in turn was replaced by Colonel Angelo R. Del Campo, 1953-1956. In June 1956 Colonel Charles L. Register began his tour of duty as the Director of BRL.

Because of the enormous expansion of staff, facilities, and program from 1945, the Director's role changed considerably from what it had been

when Colonel Simon took over in June 1941. More time had to be given to organization, coordination, and administration than before the war. This period also witnessed the retirement of Dr. L. S. Dederick in May 1953, and Mr. Robert Kent in July 1956. These two men had played a major part in the development of Ballistic Research at Aberdeen from the time of World War I.

POSITION-FINDING AND TRACKING INSTRUMENTS

When, in the course of improving rocket performance, guided missiles were developed, comparable information about their flight characteristics was needed. Wartime experimentation had shown that both optical and radar systems could be used to track rockets; during the postwar period these systems were improved, new ones were developed, and all were applied to the tracking of guided misiles. The information that these tracking systems provided was needed by the designers of both missiles and launchers, and for the preparation of firing tables.

Electronic Systems. The early systems developed by BRL for tracking rockets, which used both optical devices and radar, including Doppler radar, were sufficient for use with the types of rocket developed in World War II. However, as the development of rockets continued, these systems had to be improved and new systems were needed, especially for use with guided missiles. There were four major accomplishments in the field of electronic system development during the postwar period.

DOVAP and DORAN. The DOVAP (DOppler Velocity And Position instrumentation) system was one of the first of the new electronic systems to be developed by the Ballistic Measurements Laboratory of BRL to track a guided missile throughout its flight by noting its velocity and position at all times. Based to some extent on World War II experimentation, it consisted of a ground station that transmitted a continuous-wave signal to a missile, a receiver-transmitter in the missile by which the frequency of the signal received was doubled for retransmission to the ground, and three or more receiving stations on the ground that received the return signal. These stations also received the original signal from the ground transmitting station. The frequency of the signal from the missile received at each station was heterodyned with twice the frequency of the original reference signal, by receiving the reference signal separately at each station and doubling its frequency by the method employed in the missile's receiver. The desired beat or Doppler frequency was produced by mixing the radio frequency output from the two receivers at each station. Each Doppler frequency cycle represented a change in the length of the path, from the original transmitter to the missile to the ground receiver, of one half the wave length of the reference frequency. From the difference in the change of path length to three or more receivers, the spatial co-ordinates of a missile at any given instant could be computed by solving a group of equations representing the intersection of three or more ellipsoids. Land wires from the ground stations transmitted the Doppler signals to a common point, where they were recorded on 35-mm film for use in computing the trajectory, velocity, and other flight characteristics of a missile that was tracked.

Although DOVAP had certain limitations, mostly because of the quantity of equipment a missile had to carry, it was put to good use by BRL. It was used not only at Aberdeen but also at White Sands Proving Ground and in research conducted by the University of Michigan.

The DORAN (DOppler RANging) system for tracking missiles in flight resembled the DOVAP system in many respects. It measured velocity and range by applying the Doppler principle of frequency and phase shift to modulated radio waves transmitted from two ground stations and the missile itself and received by three ground stations. By comparing phase shift, the coordinates of a missile in space could be determined. The data obtained were recorded in three different forms: on a magnetic tape, which could be played back as a vector on an oscillograph; as a continuous photograph for a permanent record; and as a direct-inking record of missile velocity. Provisions were made for the comparative evaluation of DOVAP and DORAN data and also for comparison of the data from these two systems with data obtained by optical tracking systems.

Spheredrop. In order to eliminate some of the deficiencies of DOVAP by simplifying the system, the Ballistics Measurements Laboratory designed a comparable system called Spheredrop, which also operated on the Doppler principle. In most

respects it was similar to DOVAP, differing from it principally in that the original signal was transmitted directly from the missile itself, not from an originating ground station. Like DOVAP, Spheredrop required a number of ground receiving stations along the line of flight to receive the signals from a missile's transmitter; one receiving station in addition to those needed by DOVAP was required. This was not regarded as a disadvantage, however, because its equipment was permanently installed.

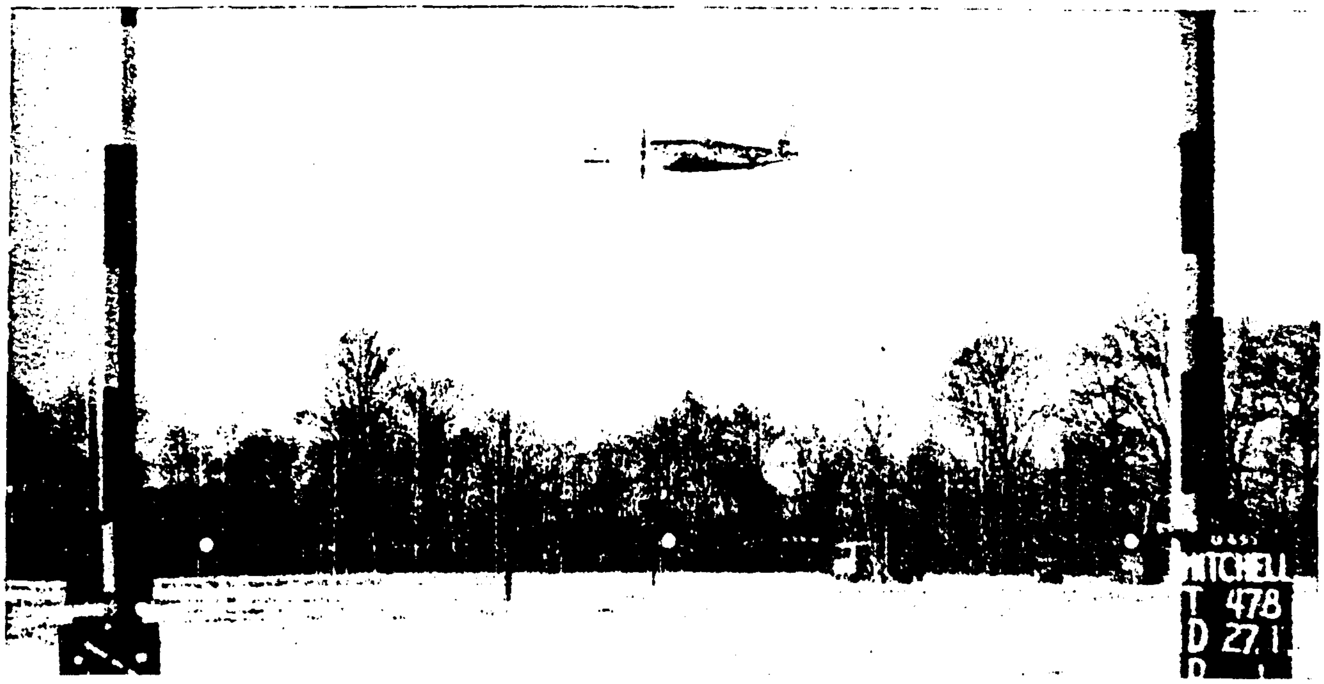
Assuming that BRL could build a stable and reliable missile-borne transmitter of the type required, Spheredrop offered the advantage that a test missile, whose space and weight limitations were very strict, did not need to mount a receiver and a receiving antenna. Some missiles, such as Loki, were too small to carry such equipment, and all missiles, regardless of size, would benefit; if they were large enough, the transmitter installed could be given a larger power output. It was hoped that the simplified design of the Spheredrop system would also reduce servicing requirements in the field.

Other Electronic Systems. Two other electronic tracking and position-finding systems were developed to assist in the analysis of guided missiles in flight. The first of these was termed the electronic missile acquisition system; it was designed to take the place of the conventional chain radar system, which had to *see* a missile from the instant of take-off and, if it lost a missile in flight, could not regain it for tracking. (The missiles considered were conventional types, without pulse transmitters or receiver-transmitters in their heads.) A missile was usually fired from a point over the horizon from the chain radar equipment used for tracking it, and its speed was so great that, without an optical tracking device properly oriented before launching, extreme difficulty would be encountered in picking it up. The electronic missile acquisition system, designed to provide the orientation needed, consisted of either an optical or an electronic tracking system at a missile's launching point, a main station near the tracker to translate the tracker's azimuth and elevation data into trajectory predictions, and connections with either an optical or an electronic tracking system, located over the horizon from the launching point, to give it these data. The data transmitted to the main tracking system were sufficient to enable it to locate a missile in flight as soon as it came within range. The progress made in developing the electronic missile acquisition system was most promising.

The second electronic device produced at BRL was originally developed to prolong the service life of the expensive drone targets used in antiaircraft gunnery practice, but was used with guided missiles as well. Termed the miss distance indicator, it determined the distance between missile and airborne target at the point at which the missile came closest to the target (for practice firings, missiles were to strike in proximity to but not on the targets provided). The miss distance indicator, developed in 1949, produced many difficulties, and by 1956 the system still was not perfected for practical use.

Optical Systems. When the problem of tracking aircraft rockets fired from moving planes arose, and when the range of rockets was materially increased, the single-station system was no longer sufficient. This situation was met by developing optical tracking systems using a series of motion picture cameras at different observation stations along the test line of flight. This general principle subsequently was followed for tracking and recording the flight of guided missiles. In some instances more precise results were obtained by optical systems of this type than by some of the electronic systems already described. This was made possible by, among other things, improvements in high-speed cameras.

High-Speed Cameras. Each of the several kinds of high-speed cameras used for recording the exterior ballistic characteristics of rockets and guided missiles had certain advantages. The Bowen-Knapp camera, for example, which had a horizontal field of view up to 600 feet in width in the object plane, was particularly useful in photographing the initial part of a projectile's trajectory, during the burning stage, and was reliable for determining acceleration rate. The Mitchell 35-mm camera, on the other hand, had a similar field of view no greater then 300 feet but could be operated



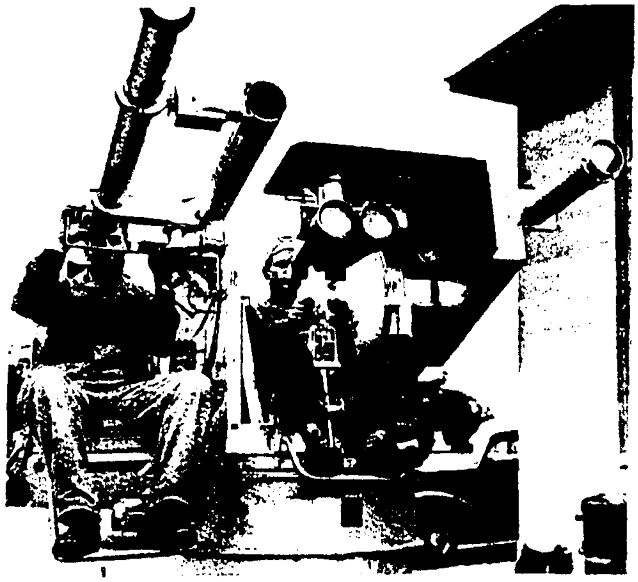
Frame of air-to-ground launch of 5" rocket photographed with 35mm high-speed Mitchell camera.

at a rate of 120 frames per second; it could record twenty successive images of a projectile traveling almost horizontally at a velocity of 1,800 fps. By properly spacing either 35-mm or 70-mm Mitchell cameras along a test line of flight, all the photographs needed for determining drag and yaw could be obtained.

The exact time at which each photograph was taken was recorded in several different ways. Most simply, a clock could be mounted before a camera in such a position that the time was recorded in the corner of each photograph. For a camera set at a fairly high angle of elevation, a small clock could be mounted on an arm extending to one side of the camera and photographed by means of a system of mirrors. Course and elevation markers were placed in the camera's field of view to determine a projectile's direction and elevation as photographed on any frame.

Although most of the high-speed cameras used for measuring trajectories had exposure rates of approximately 100 frames per second, the Ballistic Measurements Laboratory designed and subjected to preliminary testing a camera that made 1,080 exposures per second. The successive exposures were made on a single plate because use of film produced images too small for use in measuring spin. The camera was relatively simple in construction, the use of a single plate was economical, and with all data on one photograph data reduction was accelerated. On the other hand, the sky background sometimes caused complications, and timing had to be computed.

Theodolites. Considerable use was made of theodolites for tracking guided missiles. The first instrument of this type used by BRL at White Sands Proving Ground in guided missile work was the Mitchell photo-theodolite, of American design and manufacture. (Today's White Sands Missile Range Complex had its genesis as the White Sands Annex of BRL in the late 1940's.) It consisted of a sighting instrument, with a focal length of 12 inches, to which a motion picture camera with a maximum speed of 24 frames per second was attached; it was operated by an observer using an auxiliary telescope. The direction of the optical axis was recorded on each frame by dial counters operated through a gear train, and the time of each exposure was recorded by regularly-spaced pulse signals. Within the limits of accuracy imposed by



Tracking telescope mounted on M45 caliber .50 gun turret.

the design and operation, a Mitchell photo-theodolite, installed either three or six miles beyond the launching point, covered the trajectory of a guided missile to the burnout point (to an altitude of approximately 30 miles).

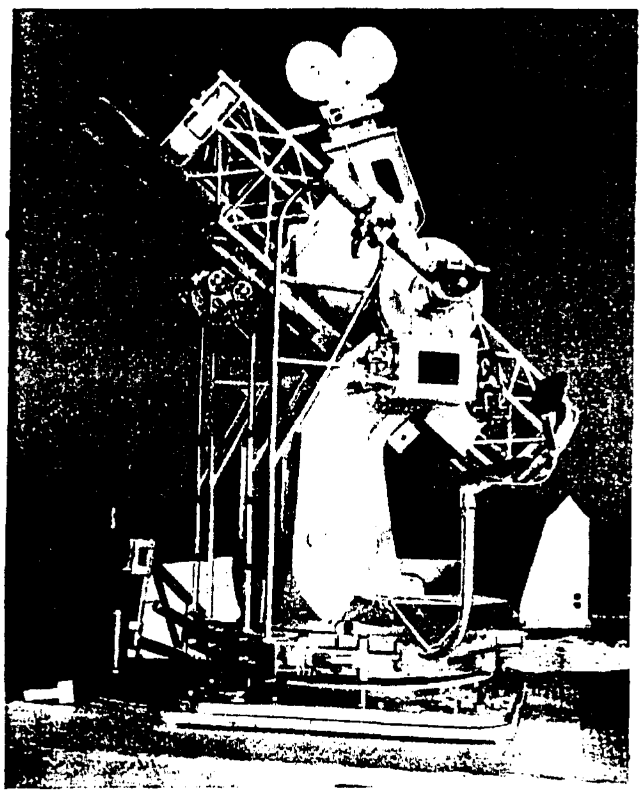
The Askania cine-theodolite, a German instrument similar to the Mitchell photo-theodolite, was subsequently put into use. It gave more accurate azimuth and elevation readings, had lenses of greater focal length and a larger film frame, and could track a missile and record data to an altitude of 50 miles.

From 1952 to 1956 BRL collaborated with the Naval Gun Factory in modifying the Askania cine-theodolite to obtain still better performance. The original modification was unsatisfactory because it did not produce good photographs of fast-moving objects, had too slow an operating rate, and was deficient in range. A second modification eliminated these deficiencies. It was fitted with a tracking device that followed a missile while still invisible, so that when the missile came into view the camera at once began to record its flight.

Tracking Telescopes. Like theodolites, tracking telescopes made it unnecessary to fit a guided missile or rocket with complex transmitting and receiving equipment to make tracking possible and permit measurement of yaw and pitch. Telescopes also permitted accurate recording of other phenomena, such as the ejection of apparatus and the separation of missile components in a stage system. If a missile was equipped to emit light signals, a tracking telescope could also be used for optical telemetering.

Tracking telescopes of different sizes were put into use. The 4.5- and the 10-inch instruments proved the most satisfactory. Each of these was mounted on an M45 caliber .50 gun turret to facilitate tracking and had attached to it a motion picture camera to record a missile's flight. Azimuth and elevation dials, as well as neon pips that indicate time, were recorded on the edge of the film for use in analyzing the recorded data. These data provided for the determination of the actual position of a missile at the moment each photograph was taken.

IGOR. By 1949 the development of the Nike ground-to-air missile had reached the point at



IGOR System

which its capability of intercepting an aircraft target could be tested, and this created an immediate demand for a means of measuring the relative trajectories of missile and target and their orientation to each other throughout an encounter. To provide these means, BRL developed the IGOR (Intercept Ground Optical Recording) system, which consisted of four mobile optical observing stations with suitable optical and recording equipment and interconnections.

Each station consisted of a 16.125-inch Newtonian type telescope with a standard Mitchell 35-mm high-speed camera; an auxiliary Akeley cine-theodolite; a special-purpose Akeley Fastax high-speed camera (for time recordings); and associated timing and communications equipment. For tracking, this equipment was mounted on a Navy Mk 19 5"/25 gun mount, which in turn was mounted on a flat-bed trailer for mobility. Tracking was done by two operators, one controlling the system in azimuth, the other, in elevation; each used a 24-inch guiding telescope for this purpose.

The four stations were placed at the corners of a 10-mile square, over approximately the center of which the missile-target encounter would occur, and maintained communication with each other by FM transceivers. The target was tracked; the required measurements were made on photographs that recorded the target and the missile as it proceeded past in its path toward the target. By comparing the measurements by each of the four stations, a high degree of accuracy was attained in determining the trajectories and relative orientations of target and missile throughout an encounter.

ITOR. At about the time BRL began the development of IGOR, a contract was awarded to the Douglas Aircraft Company for the development of an ITOR (Intercept Target Optical Recording) system. The ITOR system used clusters of four cameras at each wing tip of a target drone to give complete spatial coverage. The position of a missile relative to the target was determined by triangulation from the wing tips.

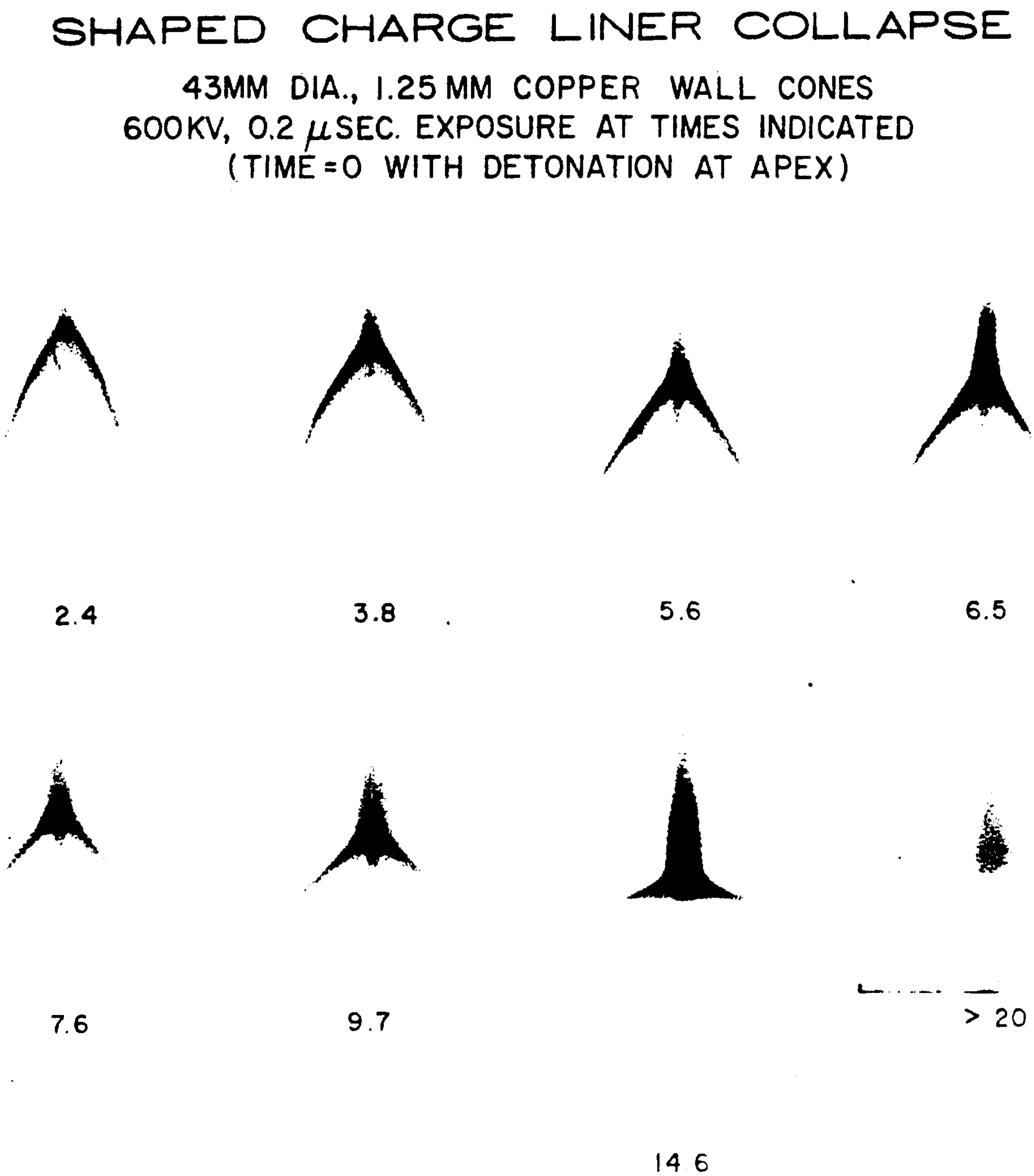
Although the ITOR system functioned satisfactorily in tests, it had certain disadvantages in comparison with the IGOR system. Equipment was lost when a target drone was destroyed in missile testing and ITOR was unable to record what happened when a missile struck its target. However, the development was more than justified as a competitive means of obtaining the instrumentation needed for analyzing target-missile encounters.

LABORATORY INSTRUMENTS AND FACILITIES

BRL was most successful in developing and improving instruments for indoor use in obtaining data needed for the design and testing of new weapons. In general, the goals were increased accuracy and the capability to provide information of a sort not previously required or available. A complete listing and discussion of all the instruments developed or improved for these purposes during this period would be far too long for inclusion here. Accordingly, only the more significant developments are covered.

Low-Voltage Flash Radiography. When the shaped charge was introduced during World War II, low-voltage flash radiography, which had been employed for investigating the phenomena of detonation, was put to use in analyzing the charge jet. Optical methods were unsatisfactory because of the jet's luminescence, and high-voltage flash radiography lacked detail because small and low-density particles were transparent to high-voltage X-rays. Furthermore, the low-voltage equipment was relatively simple, compact, light in weight, and inexpensive.

For blast and shaped charge analysis, low-voltage flash radiographic equipment was available in either of two blast chambers, each approximately 14 feet square, in a special building (frequently referred to as the shaped charge laboratory). Concrete walls three feet thick and backed by 2-inch armor plate gave protection in each chamber so that the detonation of a bare charge or the firing of a shaped charge could be



Radiograph of shaped charge explosion

viewed and its characteristics recorded. Bare charges weighing up to five pounds and shaped charges containing up to three pounds of high explosive were safely detonated in these chambers.

The placement of the radiographic equipment in the blast chambers made it possible to take three radiographs of each detonation from three different directions, 45° apart. The radiographs could be taken simultaneously or sequentially at the desired intervals. The special high-speed optical and photographic devices recorded and measured the shape and velocity of shock waves, the action of shaped charge jets, and details of other phenomena of detonation. Among the equipment provided for

these purposes were rotating-mirror and rotating-drum cameras, cameras with shutters operated by Kerr electrostatic cells or Faraday electromagnetic units, electronic image converters, and systems for spectrographic analysis.

By the use of these blast chambers, not only was the jet of shaped charges quite thoroughly studied but also a great deal was learned about the way in which different liner materials affected its formation. The stages of the development of a jet were ascertained, its velocity measured, and other terminal ballistic characteristics were analyzed.

The Transonic Free-Flight Range. Designed in 1944, constructed by 1947, and equipped with instruments for full-scale operation by the summer of 1950, the transonic free-flight range was the successor to the smaller free-flight aerodynamic range built in the basement of the main BRL building under the direction of Dr. A. C. Charters.

Interior view of transonic free-flight range

The new transonic range consisted of a building, enclosing a free-flight space, about 1,000 feet long and 24 by 24 feet in cross section, a firing station at one end of this building, and an instruments building several hundred yards away. The part of the main building nearest the firing station (about one-third of its length) was constructed of reinforced concrete; the rest was made of sheet metal on a steel frame. The firing station at one end of the main building was separated from it by a concrete-and-steel blast shield through which projectiles up to 8 inches in caliber were fired.

Screens and cameras, in groups of five, were spaced throughout the length of the range; the cameras were either on the right side or the bottom of the range, with a screen opposite each. The projectiles were magnetized before they were fired, and a solenoid coil was placed so the passage of a projectile would trigger the spark generator, which provided the illumination needed for a photograph, directly or in shadow.

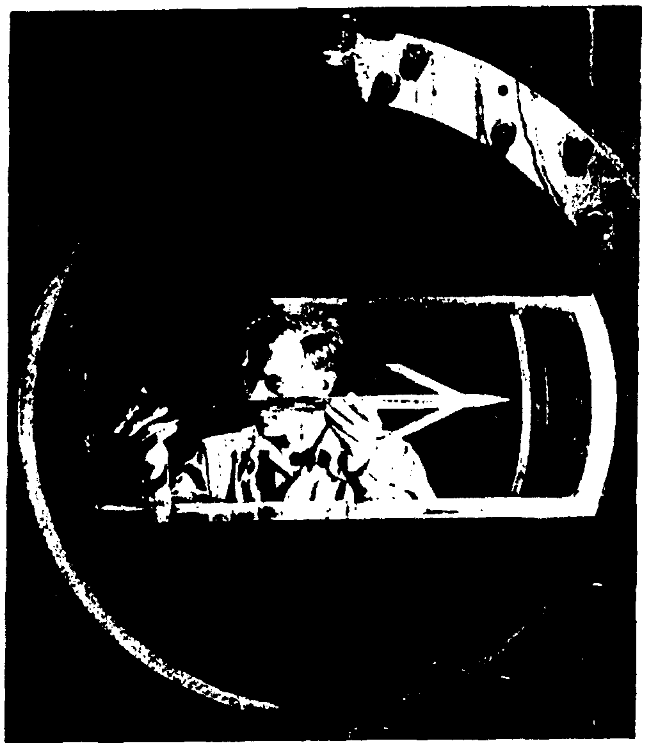
Spark shadowgraphs on photographic plates constituted the typical record obtained in the transonic free-flight range; they revealed the lines of airflow around a moving projectile and the shock waves it created. Another type of record was the direct microflash photograph, from which information about a projectile's behavior in flight was obtained. A spiral painted on a projectile's ogive, moving as the projectile rotated in flight, provided sufficient data on such photographs to make possible reasonably accurate measurement of axial spin rate.

The data obtained in the transonic range were usually reduced in high-speed computers, which provided such ballistic information as moment coefficients, coefficients of spin deceleration, lift coefficients, coefficients of damping moment, and Magnus force.

The Supersonic Wind Tunnel. The limitations of the 1945 supersonic wind tunnel were realized, and the design of a flexible-throat supersonic tunnel, to have a range up to Mach 4.4, was begun. The new tunnel was not completed until September 1947 and air speeds of Mach 4 were not attained in it until the following spring. By 1955, however, through continued improvement of the flexible-throat nozzle, operations at speeds approaching Mach 5 were possible.

Until 1951, the demands made of the 1945 and the 1947 wind tunnels for the study of guided missiles were such that these facilities were practically closed for the investigation of shell and rockets. For a number of years after V-J Day the

BRL wind tunnels were the only ones of their type and capacity regularly available to the Services, all of which were keenly interested in guided missile design and performance. Consequently, it was not until 1951, by which time a sufficient number of other supersonic wind tunnels had been put into operation elsewhere, that the load on BRL's facilities was reduced to an extent that shell and rockets could be studied.



Test chamber of flexible-throat nozzle wind tunnel at BRL.

The flexible-throat nozzle of the 1947 supersonic wind tunnel at BRL permitted a high degree of airflow uniformity, and the development of more sensitive gauges made possible more accurate measurements for use in design work. One of the outstanding achievements in this field was the installation in 1954-1955 of a completely automatic data recording system. This system recorded directly on data sheets, reducing the risk of human error and the number of test personnel required. In addition, operation of the new equipment indicated that the time required for gathering data of a typical test was reduced from 90 to about 8 minutes.

During the same period, construction began on an even more modern wind tunnel, of ultrasonic capacity, with novel features that would make possible accurate measurements of very small aerodynamic forces.

The Microwave Interferometer. Until the microwave interferometer was developed in 1953, it was difficult to obtain accurate details about the travel time of a projectile going through the tube of a gun. The suggestion that a microwave interferometer might be satisfactory for this purpose was made by Dr. T. H. Johnson, of the Ballistic Measurements Laboratory, and a number of such instruments were constructed for use at the David W. Taylor Model Basin, NPG Dahlgren, and BRL. The BRL microwave interferometer was put into use in 1953, and proved to be a most useful addition to the instruments used in the study of interior ballistics.

The microwave interferometer determined the rate of a projectile's passage through a gun's bore by means of the electromagnetic energy it directed into the gun's muzzle and down the tube's inner surface. Until a projectile was fired, this energy returned to the recording apparatus as unaffected transmitted signals. As soon as a projectile began to move up the tube, signals were reflected from its face. The changing phase relationships between those transmitted and reflected signals, which were amplified, displayed on a cathode-ray tube and photographed, were the source of the desired information about the rate of a projectile's movement. At the highest frequency employed, the interference signals showed a frequency of approximately 4,600 cps for a projectile velocity of 100 fps, or about 46,000 cps for a velocity of 1,000 fps.

The BRL microwave interferometer was invaluable in the examination of the traveling charge concept. It had the distinct advantage of being applicable to guns of all calibers for studies of their interior ballistics.

The Microwave Spectrometer. The development of the microwave spectrometer assisted materially the advancement of interior ballistics at BRL during the first ten years after the war. Its availability made possible the spectrographic analysis of the

low molecular weight products of the decomposition of nitrocellulose, the study of such asymmetric molecules as those of ethylenimine and nitromethane, and investigations of still other phenomena of gases. In addition, the spectrometer provided data about the absorption of microwaves by polar gases.

A K-band Klystron which could be tuned through the range from 21,000 to 26,000 MHz was the microwave source for the spectrometer. The klystron frequency was continuously swept at a slow rate by a mechanical drive attached to a tuner. The microwave energy thus frequency-modulated passed through a variable attenuator and a Stark-effect absorption cell, containing the gas to be studied, to a crystal detector; at the same time a 100-KHz zero-based square wave was applied to the central electrode of the absorption cell. The Stark field produced during the positive half of the square-wave cycle caused the microwave frequency to coincide with the gas absorption; the Stark field caused the microwave intensity to be modulated at a frequency of 100 KHz. A crystal diode detected this modulated microwave intensity and the resulting signal passed through a preamplifier and a phase-sensitive detector and was finally displayed on a recording milliammeter.

When the mechanical drive was replaced by an electronic sweep, microwave absorption could be displayed on an oscilloscope. Although the wider band widths required by an oscilloscope's detection system made this method of presentation less sensitive than the other, it had the advantage of facilitating adjustment of the spectroscope and speeding the scanning of the whole spectral region. Graphical display, however, was better for examining a spectral area of particular interest.

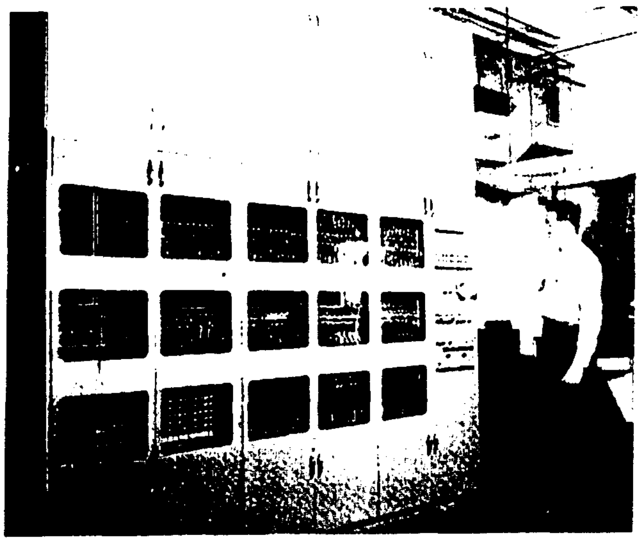
COMPUTING MACHINES

As new computing equipment became available, the other organizations at Aberdeen Proving Ground and other agencies of the Armed Services were encouraged to request their use. Thus the Computing Laboratory's primary activity was no longer restricted to the preparation of firing and bombing tables but was extended to the preparation of mathematical processes for the solution of problems. Thermal ignition, airflow around supersonic missiles in free flight, interception of bombers by missiles, war games problems, the design of new equipment for such facilities as supersonic wind tunnels and many more fields were investigated with the computers' help. The utility of the new devices was indicated by the fact that through the years after World War II they were operated at a rate of about 20,000 machine-hours per year.

The New Machines. During the first five years it was used at BRL, the ENIAC was progressively modified to increase its usefulness. Coding was greatly improved, facilitating the preparation of the problems to be submitted, reducing the time to change from one problem to another (from several days to several hours), and simplifying test procedures. As a result, from April 1948 through June 1952 the ENIAC averaged 116 hours per week in the actual solution of problems. In 1954 the memory capacity was increased 500 percent by the installation of new magnetic equipment.

The EDVAC was not put into practical operation at BRL until April 1952; however, its usefulness did not measure up to expectations. Changes were made to increase its reliability, a large external memory was added, and the installation of a photoelectric tape reader solved most of the major problems and greatly increased production rate. An IBM punched card input-output became an integral part of the system, so that the EDVAC could use information in the same form as the ENIAC. One of the major advantages of the EDVAC was the ease with which it could be changed from one problem to another.

The ORDVAC was built by the University of Illinois and brought to Aberdeen Proving Ground in 1952. It was BRL's fastest digital computer during the 1950's, capable of performing 10,000 operations per second. A variable automatic computer, ORDVAC contained approximately 2,800 vacuum tubes and 40 cathode-ray tubes; the machine itself was 30 inches wide, 100 inches high, and 10 feet long. An air-conditioning unit kept its elements cool and relatively dry, while a number of power-supply cabinets, a teletype tape-reader input, a teleprinter tape output, and an IBM



ORDVAC Computer

punched card-reader and punch completed the system. The two principal components were the memory and the arithmetic units.

In designing the ORDVAC, every effort was made to keep to a minimum the number of tubes and amount of equipment required. Its operation was improved by the addition of auxiliary memory devices. As a result of the changes, the ORDVAC averaged 123 hours per week for one year, against 116 hours per week for the ENIAC. By 1954 the ORDVAC had become the Computing Laboratory's most useful computer.

Although the new electronic computers made possible the solution of pressing problems in many different fields of ballistics, it was nevertheless true that the majority of their time was devoted to the compilation of firing and bombing tables.

THE INTERNATIONAL GEOPHYSICAL YEAR

The Ballistic Measurements Laboratory actively prepared for participation in the program for the International Geophysical Year, which began in October 1956. It designed two instrumentation systems for use in the rocket firings to be made at Fort Churchill, Canada, and, in addition, had overall responsibility for range instrumentation and logistic support at that test station. Other Laboratories of BRL took part in the upper atmosphere research to be conducted elsewhere.

One of the two systems installed at Fort Churchill was optical; the other, electronic. The optical system used photogrammetric cameras in multiple array to determine accurately the position of a missile in flight. The electronic system (DOVAP) incorporated an electromagnetic intergeometer operating at radio frequencies; it performed the same functions as the optical system.

INSTRUMENTS FOR RESEARCH IN INTERIOR BALLISTICS

As velocities of weapons increased, electronic devices were apparently the only means by which the data needed for such weapons could be obtained. Alternative devices for determining the displacement-time relationships of a fast-moving projectile in a gun tube included a telemetering instrument for obtaining signals from inside a projectile. Barium titanate ceramic and quartz crystals were used as the frequency-determining elements of a frequency-modulation pressure transducer.

Still another technique developed involved the use of radioactive sources within the test projectile. The radioactive emanations were recorded by specially-designed scintillation counters appropriately placed along a gun tube to measure gamma ray intensity at each station as a function of time.

In addition to these major developments in instrumentation for interior ballistics, several other useful devices were brought into use after the war ended. A two-color radiation pyrometer and a special thermocouple were designed for much the same purpose, namely, taking accurate readings of wall temperature inside a gun tube. Another device, developed for quite a different purpose, was the gas gun. This was an experimental device, similar to the hydrogen-helium gun developed by the New Mexico Institute of Mining & Technology and the helium gun of the Ames Laboratory of NACA. It fired projectiles at velocities up to 15,000 fps as a means of obtaining data on the aerodynamic heating of long-range projectiles and the characteristics of hypervelocity propulsion systems. It was also used to obtain pressure-time data needed in other ballistic studies. The performance of all these instruments was aided largely by high-speed, high capacity electronic computers.

IGNITER MATERIALS

BRL gave increased attention to the improvement of igniter materials as a means of developing better primers. To give satisfactory performance, an igniter had to meet three requirements. It had to be capable of transferring enough energy to a suitable area of a propellant to assure that the propellant would begin to burn properly and continue to burn after the igniter was expended. Second, it had to have the characteristics of reproducibility; that is, all primers of a given type and model had to conform very closely to the same set firing pattern. Third, an ideal igniter had to cause all the grains of a propellant charge to ignite simultaneously; however, because the ideal was not completely attainable, the igniter to be put into service had to be able to discharge its energy symmetrically to successive portions of a propellant.

Two main lines of investigation were followed in the attempt to produce primers that met all three requirements. One was a thorough study of conventional black-powder primers to improve their performance to the utmost possible. The other was the development of new igniter materials.

Black-Powder Primers. Black powder was used as both propellant and primer until the middle 1880's, after which it served as primer only. Except under unusual conditions, such as employment at low ambient temperatures with propellants of low flame temperatures, it was a generally adequate igniter material. It was fairly stable and could be stored for long periods of time without deterioration, provided it was protected from moisture. It was relatively insensitive to impact and other external forces. The two most desirable characteristics of black powder as an igniter material were ready ignition and persistence in burning once it was ignited.

On the other hand, black powder had several characteristics that made it somewhat undesirable as an ignition source for high-velocity propellants. Being hygroscopic, it could be used effectively in ignition systems only when it was fully protected against humidity. Its flame temperature was relatively low. It could be satisfactorily prepared only in granular form and, in ignition systems whose gases had to travel relatively long distances, granular materials retarded flow to an extent that they were not effective. Finally, the fact that the grains of black powder were random in shape, size, and surface conditions made it impossible for primers of this material to be fully reproducible.

Despite these shortcomings, black powder primers were sufficiently usable in many weapons

to warrant full attention to their possible improvement. Static firing tests showed that three types developed since the war were appreciably more effective than anything available before. One of these employed vents that were graduated in size so that the entire primer discharged all of its energy in a relatively short time. The second had a closing disc which prevented any of the primer gases from discharging until all the black powder ignited and burned steadily. The third, called a double-tube primer, had a hollow flash tube leading back from the percussion element to the bed of black powder; this produced very quick action because the gases from the percussion element could move rapidly over the entire length of the primer body.

Extruded Igniter Materials. Following their work in the search for better primers, BRL developed new igniter materials that could be extruded in stick form and thereby provide natural channels for the flow of gases. One such material, which also had the desirable qualities of black powder, was a mixture of potassium nitrate, sulphur, and charcoal, with nitrocellulose as a binder and small amounts of other ingredients added to aid in ignition. Preliminary experiments with this and other stick-type substitutes for black powder gave promising results.

In general, the new primers whose igniter materials were in stick form performed much more satisfactorily than even the best of the black powder primers. Their principal advantage was the appreciably shorter time they required for venting, a characteristic of much value to high-velocity weapons; the pressure waves created when venting was incomplete were a major handicap to be overcome in the development of fully-effective primers. In addition, the new primers apparently vented much more uniformly than did those of the black-powder type. The experimental compositions also continued burning even when the ambient temperature suddently dropped; this was of significance to artillery projectiles as well as rockets.

The work done with these new igniter materials indicated the practicability of designing an ignition system that would insure simultaneous ignition of all the grain surfaces of a propellant charge and at the same time be reproducible.

PROPELLANTS

The propellants used during World War II were generally satisfactory for the weapons and velocities for which they were designed. The postwar emphasis on the development of more powerful guns and rockets of much higher velocities changed the situation, however, and radical improvement of propellants became a major objective of gun and rocket design. The only way of attaining it was successful basic research into the chemical structure of propellant ingredients and intensive re-examination of the chemistry and physics of propellant combustion. Much of the Interior Ballistic Laboratory's work after 1945 produced very important results in these fields.

The Chemistry of Propellants. Many of the basic studies conducted after the war dealt with the chemical characteristics and thermal decomposition of solid propellants. The microwave spectrometer became an indispensable tool in this work; it was used successfully to identify and study the molecules of such compounds as hydrazine, ethylene oxide, methyl nitrate ammonia, methanol, and propriolic aldehyde. The findings of these analyses contributed much to a better understanding of the chemistry of propellant materials. For the most part, however, the most intensive study conducted in this general field was the investigation of the decomposition of the gaseous oxides of nitrogen.

From the studies conducted, evidence was accumulated to support the view that single- and double-base propellants, solid or liquid, burned in three distinct stages. Decomposition of the solid (or liquid) materials represented the first stage, followed by gas reactions in the dark or fizz zone. In stage three the flame reached out farthest from the propellant's surface and as much as 50 percent of the total energy of the propellant could be liberated; in this stage the liberated energy came principally from reactions involving nitric oxide. These reactions were classified chiefly as the thermal decomposition of nitric oxide itself and the reaction of nitric oxide with carbon monoxide and with hydrogen. The reactant gases in the flame zone, which were under high pressure, had an initial temperature between 1,200° and 1,500°C;

the reactions they underwent raised their adiabatic flame temperatures to somewhere between 2,400°C and 3,300°C; the maximum reached was determined by the composition of the propellant. Throughout the entire process of combustion, homogeneous nitric oxide was the determining factor. Accordingly, the kinetics and chemical pattern of nitric oxide reactions in the high-temperature range became subjects of primary interest to experts in propellants. Their principal problem was to discover which of the flame-zone reactions determined the overall rate of decomposition under any given set of conditions, and secondly, how this rate was affected by changes in temperature and pressure. More complete information on these points would suggest ways of speeding the breakdown of nitric oxide by use of additives, and this, of course, would greatly facilitate the general improvement of propellants.

Attention was also given to the thermal decomposition of hydrazine, with special effort made to determine the limiting conditions of temperature and pressure at which explosions occurred.

Closely associated with these basic researches in propellant chemistry was the attempt to develop better propellants by experimenting with various new compounds. Some of the compounds already investigated showed very promising characteristics. The one given possibly the greatest attention at that time was aminoethyl-cellulose perchlorate (AECP), which was produced by the reaction of cellulose with ethyleneimine followed by perchloration. The resulting material had a high oxygen balance and also a high explosion heat (the latter was at the low test pressures of the standard calorimeter). Two major obstacles had to be overcome, however, before AECP could be a satisfactory ingredient for propellants. The first was the insolubility of the material. In the effort to get around this difficulty, a study of propellants containing AECP was undertaken, with special emphasis given to the use of plasticizers as a means of obtaining homogeneous materials; the composite materials so formed, when made as high-percentage mixtures with nitrocellulose, burned as porous propellants. The second drawback to the use of AECP as an ingredient of propellants was its hygroscopicity; although only moderate in degree, BRL investigated possible ways to reduce it.

Other materials similar to AECP were evaluated by the Interior Ballistic Laboratory. Aminoethylpolyvinylalcohol perchlorate had many of the characteristics of AECP, including extreme insolubility in all common solvents. It differed from AECP chiefly in grain size; its grains were small. Another material, polyethyleneimine perchlorate, was soluble in a number of common solvents and probably could have been made into strands without the use of binders; however, its hygroscopicity was so great that acceptable strands could not be produced by any standard solvent extrusion process.

Experiments were also conducted with erythritol tetranitrate (ETN) to find whether it could be used as a substitute for nitroglycerine in double-base propellants. Much of the basic work on ETN was done by Picatinny Arsenal, but BRL also was actively engaged in the development. Because ETN was a solid, it was recommended as a replacement for nitroglycerin in mortar propellants; nitroglycerin froze at low temperatures and its phase-change weakened the structure of the sheet propellants of which it was an ingredient.

The Combustion of Propellants. As has been said, the search for propellants with better ballistic properties also involves basic research in the general field of the combustion process. The Interior Ballistic Laboratory gave major attention to research in the general field of the combustion process after the end of World War II. During the war enough experimental data had been accumulated to substantiate the mathematical theory of propellant combustion formulated at that time. This theory held that the combustion process had a complex dependence on initial powder temperature and pressure. If this theory were true, it offered hope that propellants could be developed whose dependence on these two factors would be minimal. Work to this end involved basic studies of the burning of powder, including identification of the chemical compounds created during combustion, the comparison of these compounds as formed by powders of standard composition with those formed by powders containing various experi-

mental additives, study of the thermochemistry of all the reactions by which such compounds were formed and consumed, and investigations of the possible ways of utilizing the data so obtained in extending the theory of propellant combustion and in predicting burning rate under different conditions. In carrying out these studies and investigations, the instruments and devices already available for use in such analysis were improved and new ones were developed to meet new needs.

It was recognized, of course, that the physical structure of a propellant, as well as its chemical composition, had much to do with the way it burned. In the effort to produce propellants with extremely high burning rates for use in the newly developed high-velocity weapons, the propellants already on hand were carefully studied. Most of them were conventional nitrocellulose-base materials in which were imbedded large amounts of crystalline materials; as a group, they were heterogeneous in structure. Most were prepared in the form of cords by a solvent extrusion process; only a few were prepared by casting or molding. Virtually all contained potassium perchlorate, with the amounts ranging from 50 percent to 70 percent by weight; other additives also were used. Most of the burning tests of the standard propellants were carried out in closed chambers with constant volumes; some were conducted in strand burners under constant pressures.

In order to predict the behavior of a propellant for a shell or a rocket, the extent of the surface on which the burning took place had to be known. For a homogeneous propellant in grain form, this area was the total exterior surface at any instant of combustion; this could easily be calculated by references to the initial shape and size of the grain and the rate at which gas was generated in the burning process. For perchlorate propellants the solution was not so readily obtained, for the role of grain form was not as simple. In grain of heterogeneous composition, layer-by-layer burning of the original surface could continue for only part of the burning period; at some point burning could move from the external surface to the interior structure via small pores and cracks that appeared in the grain.

Test results showed that at a pressure of 10,000 psi the burning rate of propellants containing 75 percent ammonium perchlorate by weight was from ten to twenty times as rapid as that of M-8 (which was 43 percent nitroglycerine in nitrocellulose) or nitrocellulose. On the other hand, the propellants containing ammonium perchlorate were found to have extremely high pressure indexes, indicating that their actual burning surfaces were greater than their external surfaces. Pressure indexes of this height (from 1.2 to 2.5) indicated a strong risk of the burning process going out of control and, if such propellants were used in a gun, the danger of the creation of excessive pressures in the chamber and tube.

Despite this most undesirable characteristic of perchlorate propellants, their other characteristics were so promising that much attention was given to any whose pressure index could be reduced to an acceptable level. As a result of the work done along these lines, at least one porous combination was developed by bonding ammonium perchlorate to laminated cotton gauze by means of a suitable adhesive. In closed-chamber burning tests samples of this propellant performed satisfactorily. This was the only rapidly-burning propellant found by BRL to have a pressure index of less than unity. Additional studies were conducted to find whether this composition could serve as a replacement for the nitrocellulose propellant commonly employed in standard weapons.

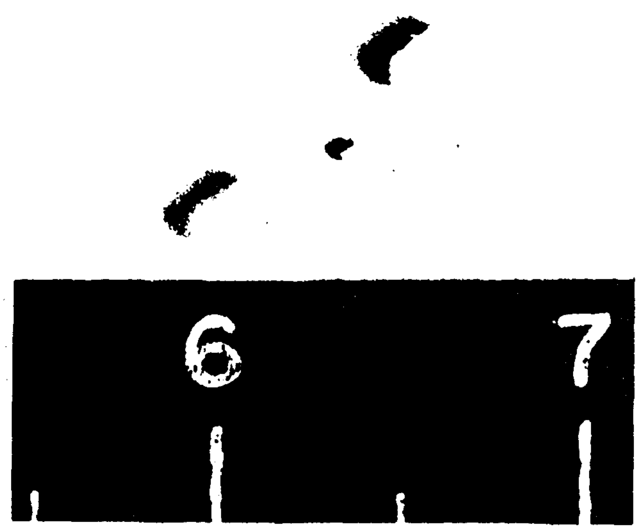
Experiments and theoretical studies were conducted to find whether the performance of propellants could be improved in yet another way. The line of inquiry led to work on composite (dual-granulation) charges. Various charges made of fast- and slow-burning compositions were test-fired with good results. These experiments were initiated when it was noted in firing tests of single-granulation charges that pressure drops occurred between the breech of a gun and the base of a propellant fired in it, and that the propellant moved forward with the projectile but at a slower

velocity. From this observation it was reasoned that the portion of a propellant nearest the base of the projectile (and therefore farthest from the breech-block) should burn faster than the portion nearest the breechblock. The experimental composite charges thus developed proved so satisfactory that a composite charge was adopted for use in the M2A1 105-mm howitzer.

GENERAL INTERIOR BALLISTIC STUDIES

The Motion of Projectiles in Guns. More intensive studies were initiated by the Interior Ballistic Laboratory to acquire precise time-travel data for the first four inches of movement of a projectile in a 105-mm howitzer tube. Conducted under the code name *Doris,* these tests consisted principally of the firing of specially-prepared projectiles at different standard loading densities; the motion of each projectile over the first four inches of travel was indicated as it touched contact points spaced at 0.1-inch intervals. The firing records show that attainment of peak pressure as a function of projectile travel varies from about 1.6 inches in the case of zone 1 firings to about 3.8 inches for the case of zone 7 firings. Detailed pressure-time and travel-time data thus accumulated and analyzed made possible the determination of velocity, acceleration, and engraving resistance for all the standard loading densities used. Information of this sort was seen to be of great value in improving the performance of ammunition in service and in developing ammunition of new design.

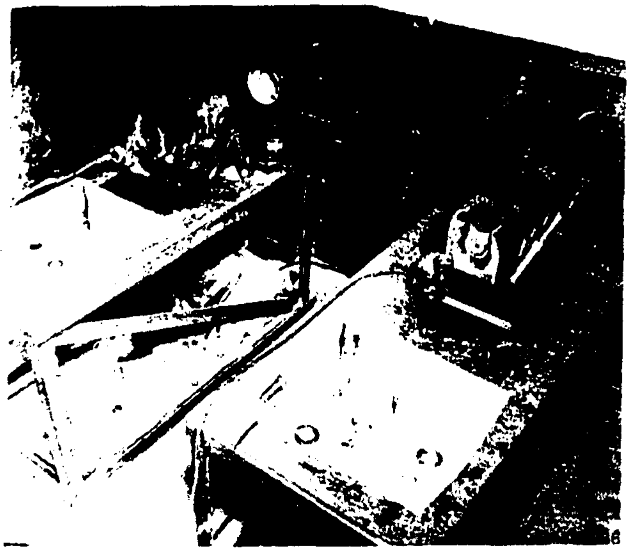
The Motion of Solid-Grain Propellants in Guns. In order to determine the extent to which a solid propellant moved in a gun during the combustion process, a radioactive pellet was inserted at a different place in each of four grains of the propellant charge of a 37-mm gun. Scintillation counters were spaced along the side of the gun's tube to record the time at which the firing pin struck the primer, the times at which the projectile moved 0.5 inch and 9.5 inches, and the forward movement of the radioactive pellets as a function of time. The data obtained were then plotted and the results were used for preparing projectile-motion curves. The principal object of this research, of course, was to provide information in terms of which rapid-burning propellants could be employed safely in guns.



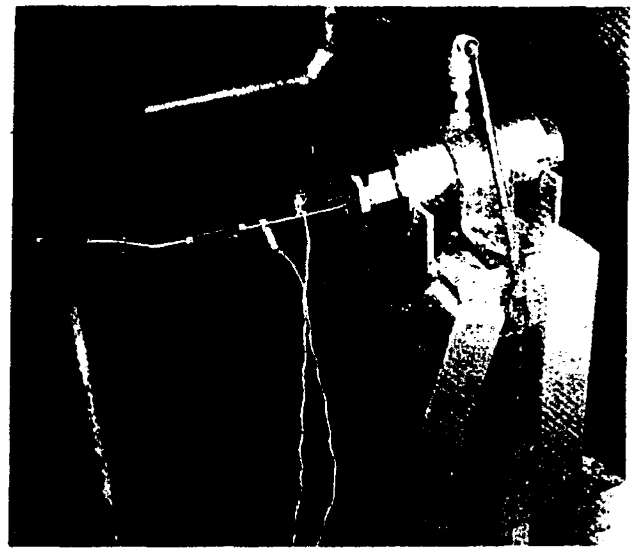
Radioactive Pellet [Center]$\sim$150 mc, [Co^{60}] Before and After Encapsulation

The Motion of Spin-Stabilized Rockets in Launcher Tubes. As part of the spin-stabilized rocket program initiated jointly by the Navy's Bureau of Ordnance and the Army's Ordnance Department in 1946, BRL began work on a series of studies to determine the motion of such rockets in the tubes from which they are fired. Much of the early investigation dealt with the problem of finding rotating-band materials that would accurately record rolling action by the rocket.

Special instruments and techniques were devised to acquire as much detailed information as possible about the interior ballistic trajectories of test rockets. One of the first methods used was to fire a spinner rocket from a magnesium tube; the scratch patterns on the inside of the tube after firing gave some indication of eccentric motion during firing. More satisfactory methods were soon developed, one of which used a radioactive band on the rocket and a film liner in the rocket tube; after



Erosion "guns" for the study of erosion of vents by powder gases.



High-pressure gas bomb for studies of erosion of vents by predetermined mixtures of hot gases.

firing, the film liner provided a continuous record of the rocket's motion in the tube. Another method used a tube of alternate bands of conductive and nonconductive materials and recorded contacts by a rocket with the conductive bands. Flash X-rays were employed for this purpose.

The data obtained by all these means were analyzed and compared. The information they supplied was extremely valuable in improving the design of spin-stabilized rockets and launching tubes, with the increased accuracy of fire as the primary goal.

Bore Erosion Studies. Bore erosion, long an ordnance problem of considerable significance, was the result of the abrasion action of high-temperature gases and propellant residues and of mechanical wear caused by the friction of rapidly-moving projectiles. It had engaged the attention of gun designers for many years, but after World War II was given increased emphasis because of the growing demand for higher velocities. Work done at BRL after the war indicated that the high temperatures produced at the inner surfaces of a gun's tube were the principal factors in erosion, and this led to research to reduce gas temperatures without a loss of velocity.

Results obtained indicated that a portion of the gases of combustion traveled with a projectile along the surfaces of the bore, and that it was the temperature of these gases which controlled the rate at which the bore's surface heated. Attempts to reduce the heating of the bore by providing cooler gases at this point indicated the possibility of lining a gun's chamber with a sheet of propellent with a low burning temperature. Tests suggested that this principle worked quite satisfactorily.

These pioneering efforts were the impetus for work at other ordnance centers (particularly in Canada and Sweden) that led ultimately to the use of additives in propellant charges — a practice that reduced bore erosion greatly.

HYPERVELOCITY GUNS

Much of the information obtained by the various interior ballistics investigations was applied in the development of more effective guns in practically every caliber group. One of the most interesting applications of the new knowledge was in the development of a traveling-charge gun, which fired projectiles at a muzzle velocity of about 7,500 fps; work on this project was undertaken in 1951.

Hypervelocity gun [experimental]

A conventional gun to fire projectiles at such a velocity was impractical, even if greatly improved propellants were available. For one thing, only a part of the chemical energy released by a conventional propellant was converted to the kinetic energy which propelled a projectile. Although it was possible to increase this energy, and therefore increase muzzle velocity, by increasing the charge-mass ratio, this required enlarging the gun's chamber and strengthening its walls; neither of these modifications was practical, for each greatly increased the mass and weight of the weapon. However, theoretical and experimental investigations indicated that a constant-pressure gun could be developed which, without significant increase of weight or size, could fire projectiles at hypervelocities.

BRL worked on the design of a constant-pressure gun; the type of gun developed was a traveling-charge weapon. The propellant used in such a gun was fixed to the projectile's base and continued to burn as the projectile was propelled through the tube. The propellant was designed to burn at an accelerating rate which increased as the velocity of the projectile increased, and thus exerted continuing pressure on the projectile to give it hypervelocity.

The first gun used in tests of this principle was a caliber .60 smoothbore; it was soon replaced by a 76-mm smoothbore gun. For the test firings both weapons were fitted with various instruments for recording breech and muzzle pressures and pressure-time and travel-time data. Certain experiments with the new type of propellant used in these guns were carried out in closed chambers. As the program developed, more and more attention was turned to the propellant in a search for the best type that would meet the unique specifications for a traveling charge. Emphasis was placed on porous perchlorate compositions, which had the high burning rates required. Most of the charges tested contained about 60% perchlorate by weight in a matrix similar to 20% nitroglycerine double-base propellant.

Although the development of the hypervelocity gun did not reach a stage at which it was possible to recommend any particular design as superior to the others, enough progress was made to indicate that such a weapon could be developed and, when developed, would be practical.

ROCKETS

One outcome of these various studies of interior ballistics was certain improvements in the design of both rockets and launchers. For example, an experimental launcher tube which tapered toward the muzzle was tested; it fired a spin-stabilized rocket which had a soft-copper rotating band near its base. As the band traveled through the tube's bore, it was compressed slightly and in the process made a tight fit throughout all its travel in the tube. Rockets so fired showed a measurable reduction of yaw on emerging from the tube and had a more

4.5" rocket leaving launcher tube

uniform muzzle velocity than conventional rockets. Continued firing tests indicated, however, that such advantages were temporary; the tube's bore was deformed after only a few rounds were fired and, thereafter, serious irregularities appeared in each rocket's trajectory. Enough evidence was gathered in the experiment, nevertheless, to indicate that accurate matching of bore diameter and band diameter, the development of better banding material, and improvement of the design of the rotating band would make possible the development of the squeeze-bore rocket and launcher as a very effective weapon.

Another series of experiments was directed toward the elimination of the defects of the closed-breech launcher, which caused spin-stabilized rockets fired from it to be unstable in flight. After experimentation and tests, it was found that flight stability could be attained by changing the cant of the rocket's fins from 11.75 degrees to 18 degrees.

Starting in 1946, the Bureau of Ordnance and the Ordnance Corps conducted a joint project for collecting basic design data for spin-stabilized rockets; the purpose was to investigate the specific factors that had to be considered in developing rockets of this type. The rocket models used in this work were constructed by BRL, and the tests were conducted on BRL's aerodynamic range. The Bureau of Ordnance analyzed the information recorded by the spark photographs taken and compiled the data. This program continued throughout the 1950's and the findings were of great value to the rocket development groups.

The theory of projectile motion advanced by Fowler, Gallup, Locke, and Richmond and supplemented by the work of Kent, Hitchcock, and McShane at the beginning of World War II accounted for all the known forces acting on a projectile in flight other than the Magnus force and moment, details of the effects of projectile shape, and certain aerodynamic factors.

The effect of drag, lift, and moment on a revolving body were sufficiently well known to make predictions and estimates accurate enough for ordinary engineering design work, but the effects of the Magnus force and moment were not predictable by the simple fluid theory which explained the other factors. (However, the Magnus force could be measured accurately by use of the spark range and the wind tunnel.) This general situation was changed during the war by the development of the theory of laminar boundary layers at BRL; marking the beginning of a procedure by which it was hoped all aerodynamic phenomena could be satisfactorily computed.

The postwar period witnessed the development of supersonic and hypersonic missiles, and ballisticians were not prepared by either experience or theoretical formulations to move ahead in the new field so rapidly as they wished. Before 1946 little had been done to relate the aerodynamics of conventional projectiles to projectiles moving at supersonic and hypersonic speeds. As a result, two of the principal problems faced by exterior ballisticians were the compilation of sufficient data to verify hypotheses, and the expansion of aerodynamic theory to make possible the accurate prediction of the behavior of projectiles and guided missiles moving at the new velocities. Much was accomplished in both fields during the first decade following the war.

RESEARCH INSTRUMENTS

The supersonic wind tunnel was one of the principal devices by which investigation of the new problems was made possible; it was used almost exclusively to study supersonic projectiles. As a result of its heavy load, wear and tear were considerable; moreover, the advance from supersonic to hypersonic missile design contributed to making the wind tunnel obsolete. Consequently, a new and greatly improved flexible-nozzle wind tunnel was put into operation for the study of hypersonic missiles. Like its predecessor, the design of the new tunnel was largely the result of development work carried out at BRL; this was particularly true of the means whereby the problem of condensation at high Mach numbers was solved. With the completion of the hypersonic tunnel, problems previously entirely dependent on theoretical studies for solution could be worked out experimentally.

In addition, a great deal of effort was devoted to improving the free flight transonic range. One innovation of considerable significance was the introduction of an optical interferometer to measure the air density fields around a model in free flight. BRL developed a technique using high-frequency light to obtain the required data, which were then resolved in electronic computers. The free flight range had very definite advantages over a wind tunnel for certain types of work. The observations and measurements it provided made it possible to determine by a single test a missile's aerodynamic characteristics, which could be determined only by a series of tests in the wind tunnel. By fitting plastic sabots to projectiles and missiles of unusual shape, such as winged missiles, finned projectiles, and bombs, specimens could be fired at the desired velocities.

THEORETICAL AND EXPERIMENTAL STUDIES

The research program put into effect by the Exterior Ballistics Laboratory during the postwar period concentrated on such problems as analysis of the effects of the Magnus force and moment, systematic investigation of the dependence of the aerodynamic coefficients of missiles in free flight on such factors as their shape and Mach number, and the characteristics of the boundary layer. As a

result of these studies, much progress was made toward an understanding of projectile motion, making possible the design of aerodynamically-stable missiles without recourse to any considerable amount of testing and retesting.

Spin-Stabilized Projectiles. One of the most important tasks of the exterior ballistician was to predict the degree of dynamic stability a spin-stabilized missile of given design would have. To accomplish this, a number of research projects were conducted at BRL.

Boundary Layer Studies. For complete understanding of the ballistic characteristics of a projectile in free flight, the motion of air around it had to be determined both theoretically and experimentally. To do this, studies were made of the characteristics of what was termed the boundary layer. It had long been assumed that the turbulence caused by the passage of a missile became laminar and remained so. It was found, however, that a supersonic turbulent boundary layer could become laminar, change back to turbulent, and then change again to laminar flow. A number of experiments were devised to prove this point, and in the process a great deal was learned about many of the factors affecting the aerodynamic stability of a missile in free flight. The accumulated data indicated, for example, that when the boundary layer in front of the shoulder of a cylinder was turbulent, it became laminar for a short distance after passing the shoulder and then became turbulent again. This phenomenon was under investigation throughout the 1950's, and a theoretical model to describe it was developed. In addition, a study of the effects of pressure gradients on supersonic laminar and turbulent boundary layers was conducted.

Three additional investigations in this field promised good results. One dealt with the thermal-lag phenomena that appeared behind the boundary-layer tripping devices used in earlier experiments; an experimental program to check a tentative theoretical explanation of these phenomena was initiated and test equipment devised. A second study which passed the preliminary design stage dealt with such thermal-lag effects in the absence of pressure gradients; the distributions of temperatures on an insulated surface downstream from a cooled isothermal surface were to be measured. The third investigation, for which general plans and theoretical studies were completed, would make exploratory measurements to assess possibility of maintaining laminar flow downstream from a turbulent-laminar transition by continuing a favorable pressure gradient. These programs became inactive however, because of the lack of personnel and the pressure of other work.

Projectile Design Studies. One of the most important aspects of applied exterior ballistics was that of predicting the dynamic stability of spin-stabilized projectiles from the knowledge of the effect of the shape of their components. The value of such information to the designers of spin-stabilized shell and rockets was obvious, for more exact information was needed to design projectiles of supersonic and hypersonic velocities.

Using the free flight aerodynamic ranges, BRL gave increasing attention to the stability characteristics of missiles that traveled at transonic speeds. The Army-Navy spinner rocket program was expanded to include the study of models at transonic velocities, in order to give systematic coverage of all projectile shapes at all velocities. The findings of this program represented the first complete determination of the small-angle static and dynamic stability characteristics of spinning bodies.

Because the firings of this program showed important transonic changes in dynamic stability characteristics, the need for transonic wind tunnel information to supplement the data from the free flight ranges became evident. Accordingly, tests were conducted to measure the static aerodynamic coefficients, including Magnus force and moment, of spinning bodies at transonic velocities. Among these were tests to determine the effect of the damping-in-pitch coefficient. Experiments using

Army-Navy spinner rocket models and the damping-in-pitch apparatus developed at BRL were conducted to explore the effects of changes in projectile configuration. Their results, together with more accurate measurements of the Magnus coefficients and the known effects of other factors, proved to be of great value to research and design.

Firing tests were also conducted in the supersonic wind tunnel and the free flight aerodynamic range to determine the factors influencing the base pressure of spin-stabilized projectiles with boattailed bodies. From the results of a number of firings conducted from 1950 to 1956, information was extracted which indicated that this would be possible. However, the data gathered were insufficient, and additional tests were planned to complete the solution.

Studies of Magnus Force and Moment. The problems of designing spin-stabilized projectiles would be simplified if mathematical formulas could be devised for describing Magnus force and moment. To this end, the Exterior Ballistics Laboratory began a large-scale investigation in 1946. Part of the work was devoted to measuring velocity distribution in the boundary layers around a spinning body in subsonic flow to obtain data to be compared with the results of theoretical small-yaw predictions. These measurements and small-yaw predictions studies continued in an effort to arrive at a full understanding of the complex flow phenomena that controlled the Magnus effects.

A limited quantity of Magnus force and moment data was obtained in the free flight ranges, but the most complete set came from the Army-Navy spinner rocket program.

Fin-Stabilized Projectiles. Projectiles stabilized by fins rather than by rotation created new problems for exterior ballisticians. Early tests at BRL showed that fin-stabilized projectiles tended to be inaccurate because it was difficult to properly align the fins with the projectile's body. This alignment failure introduced a large lift force. Experiments conducted to solve this problem indicated that fins arranged to impart a slight spin to a projectile cancelled excessive lift force and provided for more stable flight. It was also found that the permissible spin rate was within very narrow limits; if it was too slow, a projectile tumbled, if it was too fast, the Magnus force exerted undue influence and inaccurate flight.

Studies were undertaken to investigate these factors. Researchers tested a variety of unsymmetric twisted and bent fins of different configurations to find the rate of spin for each that would produce the correct amount of roll and yet maintain the desired accuracy and terminal effectiveness of a projectile. These studies, together with mathematical calculations and free-flight tests, produced data whose analysis contributed much to a better understanding of the aerodynamic forces affecting the accuracy of fin-stabilized projectiles.

Still another contribution made by BRL in this field was the so-called separated-flow theory. The phenomenon on which it was based was noted accidentally during experiments to determine the shape of the air currents flowing around sharp- and blunt-nosed projectiles. It was found that the addition of a spike, protruding from the center of a fin-stabilized projectile's nose, served the same purpose as the pointed nose of an ogival spin-stabilized projectile. The results of tests of development-type projectiles so fitted were so promising that a spike was added to a number of projectiles of this type that were adopted for service use.

FIRING TABLES FOR AIRCRAFT GUNS

The data for firing tables had to be obtained by simulated rather than actual tests so that a new aircraft would be ready for use as soon as it was introduced into service. When transonic aircraft were introduced, they imposed conditions of fire so different that completely new techniques for predicting flight characteristics of projectiles fired from aircraft guns had to be developed.

In the new type of fire, the speed of the aircraft was a major factor affecting both the velocity and the yaw of projectiles fired from guns in the aircraft. Heretofore, when the effects of aircraft speed were much less pronounced, the ballistics of such projectiles could be determined experimentally by normal ground fire; trajectories were calculated by application of a theory of small yaw verified by experiment.

From early 1954 a major part of the work of the Exterior Ballistics Laboratory was devoted to solution of this problem posed by transonic aircraft. The Free Flight Aerodynamics Branch, using the small free flight aerodynamic range, determined the small-yaw aerodynamic characteristics of two 20-mm projectiles, the T282E1 and the T306E10, the principal projectiles fired by USAF aircraft. It was impossible to attain muzzle velocities corresponding to those of a gun as increased by the forward speed of a fighter aircraft, so free flight range data were supplemented by wind tunnel tests covering velocities up to Mach 4.89; dynamic stability data at still higher velocities were obtained in the free flight aerodynamic range by constructing special light aluminum models for this purpose.

Measurement of the dynamic stability characteristics of these two projectiles indicated the mathematical model used to calculate earlier firing tables for aircraft guns was incorrect. Accordingly, the Computing Laboratory recalculated these firing tables, using a mathematical model consistent with the more accurately determined flight characteristics of the projectiles. The new tables were considerably more accurate than those they replaced.

A much more difficult problem arose in the preparation of firing tables for aircraft rounds fired at large initial yaw angles. To obtain the necessary aerodynamic data and provide means for calculating trajectories, an extensive program of wind tunnel tests was initiated and an analogue computer was obtained for exploratory flight stability and trajectory calculations.

This program, referred to as the cross-wind or large-yaw program, dominated BRL's work in exterior ballistics in the late 1950's, principally because it required the development of new techniques of measurement and research. Considerable progress was made. Five-component data giving lift, drag, pitching moment, and Magnus force and moment as functions of yaw angle over a wide range of Mach numbers were obtained by tests in the supersonic wind tunnel. In addition, the dependence of the damping-in-pitch coefficient on yaw angle and Mach number was determined for two projectiles under development.

Perhaps the most interesting test finding was the nonlinearity of the dependence of Magnus force and moment on angle of yaw. This nonlinearity, if it proved to be typical of aircraft projectiles generally, would do much to explain discrepancies between the trajectories calculated by application of the linear aerodynamic theory and those observed in the firing of artillery shell.

DEVELOPMENT AND SERVICE TESTS

To give maximum assistance to weapons and ammunition designers the exterior ballisticians at BRL devoted a considerable part of their time to service work. Models of new designs of shell, rockets, guided missiles, and bombs were tested in the wind tunnels and free flight ranges to provide data needed by designers. In addition, a large amount of troubleshooting was done to determine, for example, what caused a new shell to be unstable in flight or a new rocket to be inaccurate.

Redstone Arsenal depended heavily on the aerodynamic data obtained by wind tunnel tests at BRL in working out the design of Redstone, a surface-to-surface guided missile. To provide these data, many experiments and tests were made, using different configurations of the warhead and launcher; others were conducted to determine the characteristics that would make possible the long range desired for the complete missile. The difficult problem of giving the warhead dynamic stability after it separated from the motor was resolved principally by free-flight model tests in the transonic range. These tests were made possible by

the availability of special plastic sabots of the type developed some four years earlier for guided missile models to be fired from ordinary guns.

In a different field, tests were regularly carried out to check the flight characteristics of development-type artillery ammunition; almost all the rounds for the new artillery series, for example, were found by these means to exhibit dynamic instability as they approached the speed of sound. Guided by the results of the program on the effects of shape on the dynamic stability of shell, BRL recommended a slight change in the angle of the boattail; when this change was made, the modified rounds had greatly increased accuracy. Other ammunition submitted to service testing with comparable good results included the T108 90-mm HEAT round and rounds for the 81-mm mortar. Development and service testing of such items as the 3,000-pound bomb and many different rockets also produced excellent results.

Rockets submitted to development testing provided valuable information of fairly wide application. Certain models tested for Redstone Arsenal provided the first large-scale precision measurements of the aerodynamic characteristics that determined the stability of spinner rockets in flight. In connection with this program, live rockets with functioning motors were fired; they provided accurate data on the performance of the force system during burning. This program for rocket testing added a powerful new tool for use by the rocket designer.

Service work in connection with the atomic bomb dealt principally with the instability of early models, the reasons for which were determined by experiments at BRL.

In addition to these tasks, the Exterior Ballistics Laboratory contributed much to the development of the intercontinental ballistic missile. Most of the information for this purpose came from aerodynamic studies conducted in the wind tunnels and from various theoretical investigations.

After the end of World War II research in terminal ballistics was intensified for several reasons, only one of which was the unsatisfactory performance of certain United States Army ammunition in the conflict. The real reasons for advancing terminal ballistics to the position of a primary research field were: first, the need for increasing the destructive power of weapons to offset the greater speed, maneuverability, and defensive strength of military targets; second, the improvements in the design of weapons of all sorts made possible by the rapid advancement of military technology; and, third, the development or improvement of instruments and devices whereby more precise data about the terminal effectiveness of weapons could be obtained.

In general, the major aspects of terminal ballistics investigated most successfully after V-J Day were blast, fragmentation, and penetration phenomena; theoretical studies of other problems of terminal ballistics; and the development and improvement of the research equipment and procedures required for terminal ballistics work.

INSTRUMENTS AND DEVICES FOR USE IN TERMINAL BALLISTICS RESEARCH

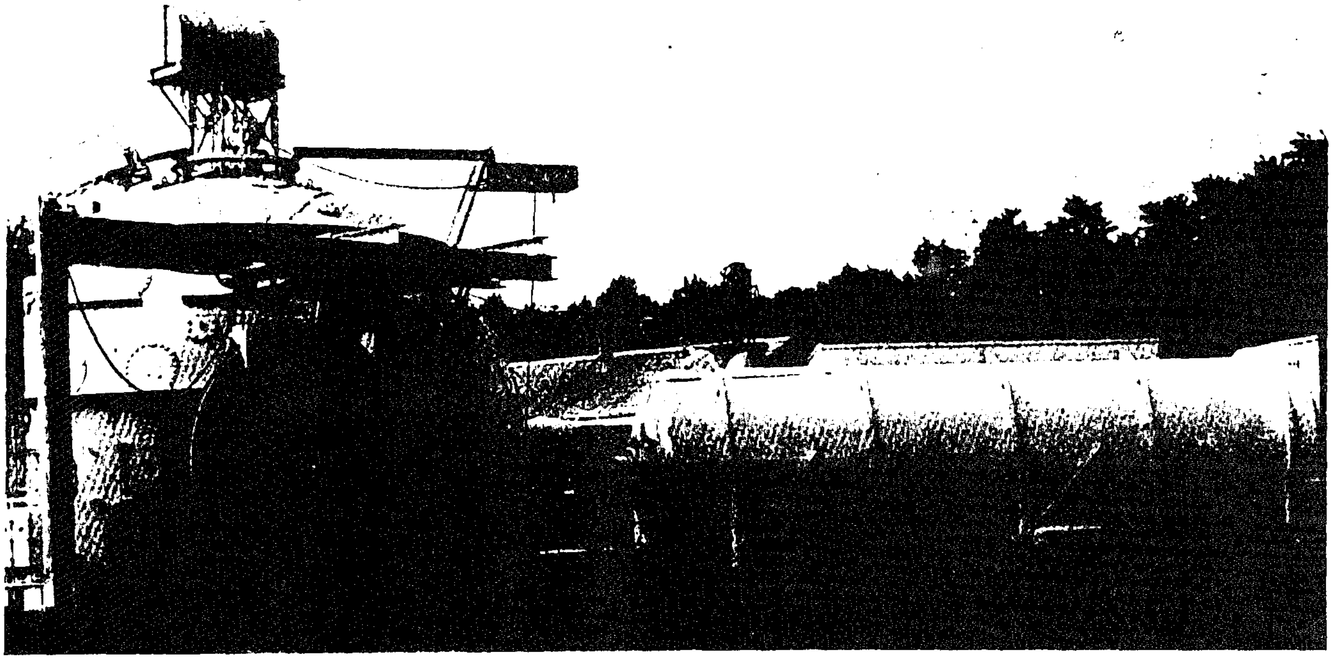
BRL specially designed a number of instruments that proved invaluable to the advancement of terminal ballistic research after World War II. One of these was an electronic *pin-technique* device for recording the time at which an object or a shock wave arrived at successive points in its forward movement. A series of charged pins were arranged along the course of the object or shock wave for which time data were desired. The moving object (or the ionized wave) was grounded so that when it contacted each of these pins a pip appeared on an oscilloscope screen. The sequence of pips were photographed by a still camera; the time of each pip was indicated by a crystal-controlled sine wave superimposed on the screen. With this equipment it was possible to investigate the initial motion of a high-velocity object or shock wave with good reproducibility, (other photographic methods were insufficient for this purpose), and to measure the velocity at which shock waves traveled through metal.

A second device was the Kerr cell camera, used to photograph both luminous and nonluminous transient phenomena at exposure times as brief as 0.5 microsecond. It was almost ideal for photographing the detonation of high explosives, the jets of shaped charges, shock waves in transparent liquids and solids, and other phenomena with propagation velocities up to 10,000 meters per second. The Kerr cell camera was especially useful in solving certain problems in the investigation of jets from shaped charges. Multiple Kerr cameras were used to take several simultaneous photographs of the same phenomenon in studying the structure of jets.

A third device, also of great value in shaped charge work, was the wire-driven projectile rotator. It simplified the problem of rotating even large-caliber HEAT projectiles at rates in excess of 350 fps; (rotation was essential to investigation of the effects of spin on the functioning of shaped charges). When used in conjunction with the low-voltage system of flash radiography, the projectile rotator made possible the examination of jets, including their velocity gradients, in more detail than otherwise possible.

For investigations of atomic blast the primary instrument was a large shock tube. With a 9-inch Mach-Zehnder interferometer and auxiliary electronic equipment installed in such a tube, it was possible to use Schlieren photography for the study of blast wave diffraction and to record the data with the interferometer. The shock tube also was used effectively in scale-model tests for study of the propagation of shock waves through orifices of different sizes and shapes and to determine gross air-blast loadings and shock wave diffraction around buildings.

For studies to determine the ballistic effects of altitude, the Aberdeen stratosphere chamber was used extensively. In it, altitude conditions of up to 90,000 feet were simulated by varying pressure and temperature. The stratosphere chamber provided valuable data on the effect of altitude on blast, ignition of fuel, and fragment velocity. Its use greatly advanced the analysis of aircraft vulnerability and increased the effectiveness of different weapons against aircraft.



BRL Altitude Chambers

BLAST AS A DESTRUCTIVE AGENT

Many studies and investigations were conducted after World War II to determine exactly the ways by which blast from HE shell and rocket and guided missiles warheads damaged and destroyed targets of different types. The work included research on the propagation of blast waves and the extent to which ambient temperature, the casing of charges, and the relative motion of projectile and target at the moment of detonation affected the capabilities of blast.

As a result of the work done at BRL and elsewhere, the details of what actually happened when an HE projectile detonated in free air were established definitely. The character of blast waves, the nature and role of the shock front, positive impulse, peak pressure (both face-on and side-on) at any point which a shock wave passes, and the effects of temperature and pressure on blast waves, were all thoroughly investigated, and the findings were systematically analyzed to provide a coherent explanation of blast phenomena. The discussion here emphasizes the phases of the investigation in which BRL played a major part.

The Effects of Altitude on Blast. Altitude had a definite effect on the capabilities of blast waves to do damage, but the majority of test firings to determine the specific effects of blast had to be conducted under ground-level conditions; it was necessary to adjust the data from test firings to the changes in air pressure and temperature found at different altitudes. R. G. Sachs, of BRL, in his theoretical investigation of this problem, developed dimensional scaling laws which converted ground-level data on peak pressure and positive impulse for use in estimating the effectiveness of blast waves at different altitudes. These laws, applied to information obtained from experiments, produce reliable determinations of the effects of altitude on blast waves produced by the detonation of explosives in free air. It was found, for example, that side-on values decreased much more rapidly than face-on values as altitude increased. It was also discovered that at 60,000 feet, for example, approximately 80 percent more high explosive was required to produce the peak pressure that a given quantity of high explosive would produce at sea level.

The Effects of Charge and Target Motion. Again the problem of adjusting test data to combat

conditions was encountered. In most of the test-firings to determine the effects of blast on specific targets, static charges were detonated against static targets. Studies and experiments showed that, for projectiles traveling at velocities less than the speed of sound, neither the peak pressure nor the positive impulse of the shock waves they produced were affected appreciably by their velocities at detonation. On the other hand, for projectiles traveling at supersonic velocities, the velocity of the charge at detonation materially affected both peak pressure and positive impulse. Because in most contemporary combat situations, attacking HE missiles fitted with proximity fuzes would be moving at supersonic velocities as they approached their targets, the resultant intensification of peak pressure and positive impulse had to be taken into consideration when evaluating their destructive capacity, especially when used against fast-moving aircraft.

Tests to determine the increase of blast effect as a function of charge velocity at detonation were conducted by BRL, with generally useful results. At the same time a parallel experimental program to determine the effect of target motion (especially aircraft speed) on the damaging capabilities of the blast waves from HE charges was also conducted. In this program, BRL worked with Naval Ordnance Test Station China Lake, California, using the supersonic Naval Ordnance research track (SNORT) for the tests. Much data were recorded. It was found, for example, that a blast wave whose peak pressure was 10 psi exerted the same incident peak pressure on a target moving toward it at a speed of Mach 0.5, as a blast wave whose peak pressure was 20 psi exerted on a stationary target. Most of the tests were conducted with B-29 stabilizer and wing components; plans were prepared to conduct similar tests using comparable components of B-47's.

The Effects of Casing on Blast. Still another aspect of the investigation of the blast problem was the effect of the type and weight of a charge's casing on the blast wave produced by detonating the charge. The reduction of peak pressure and positive pressure resulting from the use of any type of casing was noted, of course, but the interrelationships among charge weight, composition of the explosive, material of the casing, and weight (thickness) of the casing were very complex insofar as they affected this reduction. The experiments conducted indicated that the mass (thickness) of a casing, rather than the material of which it was made, was the critical factor.

The Effects of Blast on Aircraft. The destructive capabilities of the blast waves produced by HE shell, rockets, and guided missiles were significant to ordnance research primarily in terms of the use of such weapons against aircraft. From 1946 BRL actively supported a broad program to increase the effectiveness of antiaircraft and aircraft weapons, on the one hand, and to investigate the vulnerability of aircraft to ordnance weapons, on the other. In both phases of this program considerable emphasis was placed on both external and internal blast as damaging agents. A great deal was learned during the first decade of this work.

Investigations of External Blast. To obtain the data needed, both static and dynamic firings of bare and cased HE charges were made against at least eight different aircraft types (B-17's, B-25's, etc.), against components of these aircraft types, and against replica targets representing their fuel cells. The data, gathered and analyzed in relation to information about the characteristics of blast waves learned in other programs, enabled investigators to estimate quite accurately the effectiveness of blast from missiles detonated outside aircraft in disabling or destroying specific aircraft types. The results of such analyses were usually presented as closed curves drawn around a given aircraft's profile, enclosing the area within which the detonation of an HE charge, of given weight and other characteristics, would have a high probability of destroying that aircraft. These curves were called blast contours. Work was continued to make them more accurate and reliable.

Investigations of Internal Blast. The damage done to an aircraft by an HE projectile detonated within its airframe was given as much attention by BRL as was damage from external blast. A wide variety of firing tests that used, for the most part, bare

charges of TNT, were devised and conducted with aircraft and aircraft components of all available types. Such charges were normally detonated statically about six inches beyond the aircraft's skin; this was approximately the point to which an HE projectile with a slight-delay impact fuze would penetrate before detonating. After a charge was exploded, assessments were made of the damage. Because such tests could not simulate actual combat conditions, methods were developed whereby the results of static tests could be used to estimate the type and extent of damage that would be done to an aircraft in flight by a moving projectile.

Several theories were developed by the aircraft vulnerability analysts to determine the extent to which the relative motion of an HE projectile and a combat aircraft in flight affected the degree of damage done. The total energy theory was the one most commonly used. This stated that the total energy expended within a moving aircraft by the detonation of a moving HE projectile consisted of the chemical energy generated by detonation of the HE charge plus the kinetic energy of the projectile's metal parts at the moment of detonation. By using this theory, it was possible to determine the quantity of bare TNT, detonated inside an aircraft, that would cause damage equal to that which would be inflicted by the detonation of a given moving HE projectile. This quantity was referred to as the equivalent weight of TNT; in other words, the weight of a bare TNT charge that would do the required damage. A formula was developed for calculating the equivalent weight, and it was used in the preparation of nomographs for ready reference.

Although useful within recognized limits, the total energy theory oversimplified the problem of predicting internal blast damage because it failed to take into consideration such factors as a projectile's direction of flight, its exact position at detonation, its shape and charge-metal ratio, and the detailed characteristics of the target aircraft. For this and other reasons, work continued to refine the total energy theory for more effective application.

Estimates of specific damage by internal blast from a variety of bare and cased charges were made for a large number of Air Force and Navy planes, including those used in the external blast tests. As in external blast work, such information was constantly employed in designing more effective ammunition for use against aircraft and in determining the vulnerability of aircraft already in use and under development.

Gust Effects on Aircraft Structure. For several years BRL investigated the phenomenon termed gust effect, which resulted from air molecules behind the advancing shock front of a blast wave from an externally-detonated HE charge having a high radial velocity (called the material velocity) away from the center of detonation. In consequence, gust loading, which had a high energy level, was imposed on an aircraft immediately after the shock front passed it. This loading had a very brief application time; it acted as a high-intensity sharp-edged gust which began at a high positive level and then decayed exponentially, passing through zero velocity into a negative phase. It attacked an aircraft as a typical atmospheric gust and, if very severe, could disrupt the aircraft's stability or rotate it by passing across either wing or tail surfaces. Work continued at BRL on this gust loading problem.

ATOMIC BLAST STUDIES

As early as 1946 a Nuclear Physics Section was organized in the Terminal Ballistics Laboratory to make fundamental studies of the processes and techniques used in nuclear research. The members of this section continued their investigations throughout the 1950's, and maintained close working relationships with scientists in other research laboratories, both Government and private. By these means BRL gained access to information about the latest developments in the nuclear field, much of which was put to use in the development of new nuclear weapons. As part of this work, BRL participated in most of the nuclear bomb tests conducted in Nevada and the Pacific.

Participation in Nuclear Blast Field Tests. BRL had important assignments in Operations Buster-Jangle and Tumbler-Snapper in 1952, Operation Upshot-Knothole in 1953, Operation Castle in

1954, and Operation Teapot in 1955. Although the work for these operations varied, the principle function was to provide instrumentation. In Operation Buster-Jangle, for example, BRL cooperated with the Naval Research Laboratory in developing and providing all instrumentation for measuring air blast, shock velocities, and hydrostatic pressures. The data obtained provided a detailed picture of atomic blast phenomena and contributed much to an evaluation of the effects of atomic blast near and under the surface of the ground.

In Operation Upshot-Knothole in 1953 BRL measured the effects of air blast on structures. Data on peak pressures, pressure-times, strain, and displacement were analyzed for use by the appropriate agencies of the three Services. A considerable number of the Computing Laboratory's personnel were required for computing these data; in all, it took thirty people six months to complete the calculations. After this was done, the recording equipment was modified for future work in terms of what had been learned, and some distinctly improved pressure-time and dynamic overpressure gauges were developed. Similar work was done in the nuclear tests conducted after 1953.

BRL had other responsibilities in most of these tests. In Operation Upshot-Knothole, for example, personnel analyzed data obtained from the Ordnance equipment exposure test, designed to determine the type and extent of damage that nuclear blast did to various Ordnance weapons and vehicles. The results of these tests were reduced to probability-of-damage curves for all items of Ordnance Materiel that had been exposed to nuclear blast.

Tests of Protective Shelters. Shock tubes were used extensively at BRL for testing models of buildings of varying design and construction to determine air blast loadings and the diffraction of shock waves about such structures. These tests produced valuable data for use in designing protective shelters for people; the information was turned over to the Corps of Engineers and the Atomic Energy Commission. Other tests obtained comparable information for protective structures for animals, aircraft, and reactors.

Effects of Nuclear Blast on Troops. In the latter part of 1955 BRL was requested by Headquarters, CONARC, to conduct research on the primary and secondary effects on troops of air blast from nuclear weapons. The BRL work was to be part of the larger program in participation with the Army Medical Corps, the Medical Laboratory of the Army Chemical Center, and the Human Engineering Laboratory of Aberdeen Proving Ground. The program was coordinated by the Civil Effects Test Group, the Atomic Energy Commission, the Quartermaster General, and CONARC.

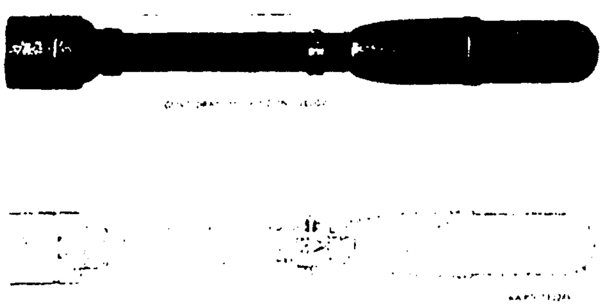
The overall program called for thorough investigation of the mechanics of injury by blast. Its purpose was to improve the means by which the psychological hazard induced by blast could be estimated and offset by dissemination of specific information about what could be expected. BRL's primary function in the program was to provide the facilities for producing air blast. These plans called for the employment of the shock tube technique.

Effects of Dust-Laden Air on Nuclear Blast. Both laboratory and field tests were conducted by BRL to determine the effect that dust in the air had on blast waves produced by nuclear action. By use of a heavy concentration of finely-ground bentonite, reduction of the velocity of sound by as much as 3.7 fps over a distance of 10 feet was measured in shock tube tests. It was found that, as the concentration of dust in the air decreased, the velocity of sound increased until it reached the free air value. To work on this problem, BRL devoted substantial time to the development of special gauges for use in the research.

SHAPED CHARGES

The cavity-lined or shaped charge was first used by Allied forces in standard service rounds in the North African campaign of 1942. Although employed in artillery shell as HEAT rounds, it was most widely and successfully used in fin-stabilized rocket-type projectiles such as were fired in the shoulder-held bazooka. Despite considerable success with such weapons in combat, the use of the shaped charge principle remained relatively restricted. This was because the development agencies did not yet fully understand all the factors

involved in the formation of the shaped charge jet, the many difficulties encountered in manufacturing satisfactory shaped charge ammunition, the relative inaccuracy of shaped charge weapons at all but short ranges, and a general inability to get good results when firing shaped charge ammunition from rifled weapons. As a result, a major new field of research and development was opened.



HEAT round for bazooka

Basic Research. An intensive research program to obtain the information needed to understand the formation and performance of effective shaped charge jets was initiated in 1946 by Army and Navy agencies and Government contractors. BRL participated actively in this work, with even greater emphasis during the 1950's.

The program provided the basic data needed to identify and evaluate the factors that determined the performance of shaped charges. The relationships between the angle and diameter of the cone, on the one hand, and standoff, on the other, were well established, as was the way in which standoff affected the penetration capabilities of a shaped charge shell or rocket. It was determined that a shaped charge jet contained a relatively small group of discrete hypervelocity fragments from the cone that traveled at velocities from 15,000 to 30,000 fps, and that the total number of these fragments depended on the size of the charge, the angle of the cone, the thickness and material of the liner, and many other factors. The masses and velocities of the fragments were governed by the same factors. Studies continued for several years after the war to refine this information.

BRL conducted several sets of investigations in this phase of shaped charge work. For one thing, in studying the different metals of which shaped charge cones could be made, it found that copper, steel, and aluminum, in that order, had the most desirable characteristics. This work continued with considerable attention given to alloys. Metallurgical investigations were made to determine what general properties of metals (hardness, melting point, boiling point, ductility, and tensile strength) had an appreciable affect on the penetration capabilities of shaped charges.

Research to Increase the Effectiveness of Shaped Charges. From 1953 to 1956, the BRL phase of the shaped charge program was given a new emphasis. More and more attention was directed to investigations of the possibility of controlling the spin of shaped charge projectiles fired from rifled guns to prevent loss of penetrating capabilities as a result of spin; increasing the damage potential of shaped charge weapons after armor plate had been perforated; devising effective defense against shaped charged weapons; and systematically disseminating information about shaped charge research and development work so that all the agencies participating in the program could keep fully abreast of the progress being made in all aspects of the work.

Increasing Penetration Capabilities. The principal studies of means to increase the penetrating capabilities of shaped charge weapons used against armor were centered on the determination of optimum rate of spin. It had been found that early HEAT shell such as were fired in World War II, lost from 30 percent to 50 percent of their penetrating ability because their relatively high spin rates disrupted the molecular structure of the shaped charge and caused the jet to diffuse when a shell hit armor, dissipating much of its energy. As soon as the war ended, intensive studies were undertaken to remedy this situation. In 1950 the wire-driven projectile rotator was developed at BRL to facilitate study of the effects of spin on penetration capabilities.

The optimum rate of spin (controlled by the use of fins to stabilize shaped charge projectiles in flight) was determined, and there were indications that a cylindrical in place of a conical liner would provide major advantages in this respect. The

detailed design of this new liner began in 1955, and fluted conical liners were also tested. All indications showed that advances in shaped charge design, to facilitate the penetration of armor, would be made.

Increasing Effectiveness of the Jet After Perforation of Armor. Designers of shaped charge found it necessary to increase the damage potential of such weapons after a target's protective armor had been perforated. A number of different means to accomplish this were devised and tested, including placing a steel cap at the base of the shaped charge cone and filling it with a number of small steel cylinders. These cylinders followed the jet through the hole it made in armor, where they functioned as preformed fragments to do damage, for example, within the crew compartment of a tank. This method added little to the effectiveness of shaped charge weapons, for the cylinders followed closely the trajectory of the jet and were definitely restricted as to the area in which they were lethal.

A second method was to incorporate chemicals, such as GB gas, in shaped charge rounds so that the gas, either free or in a container that burst on impact would follow the jet through armor and incapacitate enemy personnel. In the late 1950's this method was still in the preliminary design stage.

A third method employed a conical sleeve of either S-50 aluminum or magnesium which fit snugly over a projectile's cone. It disintegrated when the basic jet was formed, and provided incendiary particles that followed the jet through armor. Preliminary investigations indicated that such construction doubled the area within which a jet was effective and at the same time greatly increased its incendiary action.

Defense Against Shaped Charge Rounds. As in practically all ordnance developments, full attention was given in the shaped charge program to devising effective countermeasures against shaped charge rounds an enemy could use against our forces. Special emphasis was placed on the protection of armored vehicles. The experiments conducted included the use of spaced, laminated (including layers of such materials as glass), spiked, and explosive armor. Experiments by BRL indicated the possibility of reducing the effectiveness of shaped charge projectiles by as much as 60 percent by one or another of these means.

Dissemination of Information about Shaped Charge Work. Throughout the shaped charge program, particularly from 1950 to 1956, BRL placed much emphasis on the dissemination of information about shaped charge research work. This included symposia conducted at BRL and elsewhere, the organization of a permanent Shaped Charge Steering & Coordinating Committee at BRL in 1954, and the publication in 1954 of BRL Report 905, *Critical Review of Shaped Charge Information.* This report was considered generally the most authoritative guide to shaped charge work done to the time it was compiled; it contained excellent articles by thirteen specialists from BRL, Naval Ordnance Laboratory, Carnegie Institute of Technology, National Bureau of Standards, and the Firestone Tire & Rubber Company.

FRAGMENTATION STUDIES

Together with blast and shaped charge jets, fragments from projectile casings constituted the three principal damaging agents of ordnance weapons. Accordingly, in 1947 BRL initiated a major program for research to cover all aspects of fragmentation as a means of increasing the effectiveness of fragmentation-type weapons. This program continued through 1956 without interruption, and provided some very valuable information for use by ordnance designers.

The Physical Properties of Fragments. The effectiveness of every type of fragment emitted by an HE projectile was determined by the application of mathematical formulas based on both theoretical and empirical data and checked as far as possible by test firings. The capabilities of fragments to do damage depended largely on their mass, striking velocity, and residual velocity, all of which could be computed for practically every situation. It was determined the extent to which velocity would be lost when a fragment passed through air, liquid, metal, other materials, and bone and tissue.

Concurrently, other studies were conducted to

determine the effects of the various HE compositions used in fragmentation rounds on the size, mass, and velocity of the random fragments emitted on the detonation of an HE projectile. Comparative studies were made of the fragmentation capabilities of such compositions as HBX-6, Torpex, Composition A, and Composition B when used as filler for different types of projectile casing.

Preformed and Controlled Fragments. To increase the effectiveness of fragments from HE warheads of rockets and guided missiles, both preformed and controlled fragments were developed. The first of these were individual metal fragments either imbedded in, taped to, or otherwise arranged around the HE filler of a thin metal casing for either a rocket or a guided missile; BRL experimented with spheres, cubes and rods (the last were generally from 3 to 6 inches long). Controlled fragments, on the other hand, were fragments whose size and shape were determined by the design of the rocket or guided missile casing. The techniques employed to produce such fragments included providing a pattern of lines of weakness in either the interior or exterior surface of a casing of normal thickness; winding notched wire around a thin metal casing; building up a casing of a series of notched rings; and building up a casing of notched wire bars. BRL tested HE shell of most of these designs to determine their terminal ballistic effectiveness.

Although these principles of HE projectile design were fully applicable to the warheads of rockets and guided missiles, the high pressure exerted on the casings of gun-fired shell made it necessary for some other means to be adopted to increase the effectiveness of their fragments. Two major lines of development were followed. The first of them led to the design of multiwalled shell. Double-walled shell had approximately 25 percent greater effectiveness than conventional shell because of the greater number of fragments emitted and also had a greater uniformity of fragment size within the range desired. BRL also initiated development of shell with three and more walls.

Greater advantages were obtained, however, as a result of studies of the fragmentation characteristics of different metals and alloys that began at BRL in early 1948. Detailed analysis of many metallic materials indicated that cast iron ranked very high in desirable fragmentation characteristics. This conclusion was substantiated by reports, received in 1950, of the unusual amount of damage done to United Nations personnel by fragments from the North Korean 120-mm mortar shell, which had a cast iron casing. The design of new shell of this type was facilitated by the appearance of ductile cast irons on the American market at about this time. These were referred to as nodular irons, and their fragmentation characteristics were much better than those of ordinary gray cast iron. These new ductile and malleable cast irons were used in the fabrication of experimental HE shell which, when tested, proved superior to comparable shell whose casings were made of either cast or forged steel or gray cast iron. Despite the inability to obtain a nodular iron of the ductility required for artillery shell, it was anticipated that this general development could yield good results in the future. However, questions were raised of both the capacity and the ability of the casting industry to produce such shell in the large quantities needed if the development proved to be completely satisfactory.

Fin-Stabilized Darts. A study was made at BRL of the feasibility of developing rocket and guided missile antipersonnel warheads loaded with fin-stabilized darts surrounding the HE filler. Theoretical calculations indicated that such a warhead would have a lethal area from two to five times greater than that of a comparable warhead containing preformed metal spheres. The development progressed to a point at which a 35-pound warhead containing 3 pounds of Explosive D and a number of 15-grain metal darts was test-fired. Although the darts were given an initial velocity of about 1,000 fps on detonation of the warhead, and were stable in flight, very little damage was done by them. This initial test was nevertheless sufficiently promising for the project to be continued.

INCENDIARY AND COMBUSTION STUDIES

In the field of incendiary ammunition, which was of great importance for use against aircraft,

BRL's studies and investigations followed three main lines: study of the characteristics of incendiary agents, analysis of the combustion properties of fuels, and investigation of the physical properties of fuels.

Many tests were conducted to determine in detail how and under what conditions an incendiary projectile or fragment ignited fuel in aircraft or elsewhere: the findings were of special value to the aircraft vulnerability program because fire was a very effective means of killing combat aircraft. The types of ignition agent evaluated in these tests were ordinary steel fragments, pyrophoric fragments (metal fragments containing special incendiary compounds), experimental fragments of titanium and aluminum, AP and API bullets, AP shot, and HE and HEI shell. The tests were conducted under ground-level and simulated high-altitude conditions. The data produced were supplemented by information from combat rounds and USAF accident records. On the overall basis thus provided, probabilities of aircraft kill by fire were calculated for a number of types of U.S. ammunition.

A number of fuel flammability studies were conducted to determine the flammability and explosive characteristics of fuel vapors under all anticipated conditions. The data obtained were utilized at BRL in the development of a three-dimensional model for the ready determination of the flammability limits of any given fuel under all reasonable combinations of ambient atmospheric pressure and temperature. It was expected that this model, when perfected, would make possible the easy extrapolation of the desired data from what were already available.

Other incendiary and combustion studies were concerned with the capabilities of antitank projectiles and napalm bombs in producing fires in the compartments and engines of armored vehicles.

PENETRATION STUDIES

Several years after World War II ended, BRL developed a theory of penetration to clarify and simplify the overall problem of determining the probability and extent of armor penetration by different missiles. Well-established force equations were used as the starting point; the assumption was made that a constant force resisted a projectile throughout its penetration of armor. Working from this basis, it was possible to develop formulas for determining ballistic limit, residual velocity, and critical angle of ricochet. Results from application of these predictive formulas were in remarkably close agreement with the predictions obtained by applying formulas based on test data.

WOUND BALLISTICS

During World War II work on wound ballistics concentrated chiefly on the relation between the volume of the cavities missiles formed in animal targets and the physical and impact characteristics of the missiles. However, the finding of these studies could not be used as a basis for estimating the probability that a wound inflicted on a man by a missile would be incapacitating. This was the type of information, reduced to quantitative form, that was needed.

In 1941 Burns and Zuckerman in Great Britain had made a more refined analysis of the quantitative requirements of wounding than was represented by the 58-foot-pound rule, and in 1944 R. W. Gurney of BRL had suggested that mv^3 was a usable criterion. Studies such as these were of the needed type, but they were not carried to a point at which their findings would be of practical use. In 1945 J. H. McMillen and J. R. Gregg of Princeton University's Department of Biology investigated severe and fatal wounds caused by projectiles reaching certain vital body regions after perforating skin, soft tissue, and bone; the condition imposed for classifying the wounds as severe or fatal was that the residual velocity of a missile on reaching a vital region had to be 7,500 centimeters per second or more. The conclusion derived from these studies was that a random hit by a steel ball either 0.666, 0.125, or 0.25 inch in diameter, striking from either the front or back at the minimum velocity required to meet the imposed condition, would cause either a severe or a fatal wound. Plotted against the probable striking velocities of such missiles, the resulting probabilities were on the whole roughly in agreement with the earlier conclusions of Burns and Zuckerman.

Aware of the inadequacy of these criteria for

practical application in wound ballistics analysis, BRL asked the Biophysics Branch of the Medical Laboratories, Army Chemical Center, to conduct test firings against live animals to obtain experimental values for the probability of personnel being incapacitated by fragment hits. This was done and the obtained data were analyzed by BRL to produce a formula that could be applied to the wounding of human beings. It was assumed that the residual energy a fragment must have on reaching a vital region of the body was $2.5 \cdot 10^7$ ergs (approximately 1.8 foot-pounds). The results of this formula furthered the development of wound ballistics.

As with most of the other work done by BRL during World War II, there was little opportunity for conducting extensive research of the overall combat effectiveness of weapon systems. The effect-of-fire studies conducted were concerned principally with the fragmentation characteristics of shell and bombs and the attainment of penetration data for individual rounds of ammunition. However, the combat effectiveness of many weapon-ammunition combinations in the war itself left much to be desired, and the need for increasing the effectiveness of the aircraft, antiaircraft, and antitank weapons was so apparent that, as soon as the war ended, major attention was directed to the analysis of weapons effectiveness. The programs initiated included aircraft and armored vehicles vulnerability studies, investigations to increase the effectiveness of weapons already in service use, and other investigations to make possible the development of greatly improved weapon systems. This phase of BRL's activity increased significantly during the postwar years so that in 1952 a new major unit, the Weapon Systems Laboratory, was organized to conduct it.

VULNERABILITY STUDIES

Although some work had been done at Aberdeen Proving Ground before and during World War II to obtain data about the vulnerability of combat aircraft to ordnance weapons, a systematic program for this purpose was not put into effect until July 1945, when OCO directed that investigations be initiated to determine the optimum caliber for aircraft weapons. Actually, much of this work was supported by the U.S. Air Force. This optimum caliber program was the forerunner of the several weapons effectiveness and vulnerability programs that BRL conducted. In March 1946 it was supplemented by a project to determine optimum characteristics for aircraft and antiaircraft weapons. Then, in April 1947, a project was initiated specifically to determine the vulnerability of combat aircraft and guided missiles to ordnance weapons; the findings were applied to the design of aircraft and missiles, to reduce their vulnerability, and also to the design of aircraft and antiaircraft weapons, to increase their destructive power.

Within the next few years the weapons effectiveness field was expanded to evaluate weapons and weapon systems of all types and to determine the vulnerability to ordnance weapons of armored vehicles and other group targets.

Aircraft Vulnerability Studies. BRL's aircraft vulnerability program was the most extensive of its kind conducted in the world. The majority of the data it produced was for Air Force use, some test work was done for the Navy, and much of the information gained was employed by BRL in weapons evaluation studies.

The aircraft vulnerability program consisted principally of three major types of research and development work. First was the devising of procedures for measuring the vulnerability of various sorts of aircraft components to different ordnance weapons. Secondly, the procedures developed were applied in experimental and test work to obtain the detailed data required. Finally, on the basis of the gathered information design changes were recommended to increase the passive defense of combat aircraft against ordnance weapons; these were made available to the USAF authorities charged with the procurement of aircraft and to aircraft designers as well.

Procedures for Estimating the Vulnerability of Combat Aircraft. Early in the aircraft vulnerability program it became apparent that, however desirable it might be to have up-to-the-moment targets for test firings, obsolete aircraft of World War II types would serve adequately for the compilation of vulnerability data. The major objective was the formulation of design principles for passive defense of sufficient universality that they could be applied to combat aircraft generally, especially to aircraft still in the design and development stage. Special recommendations for the passive defense of specific aircraft were regarded as secondary to this main mission.

For the purposes of vulnerability analysis, a combat aircraft was regarded as a unit made up of four major components — a structure, fuel system, power plant, and personnel. The vulnerability of an aircraft to a given weapon was determined by analyzing the vulnerability of each of its com-

ponents to that weapon under various conditions and directions of attack. Damage was assessed on the basis of whether it was sufficient to force the aircraft out of control, prevent it from completing its mission, or make impossible a safe landing on return to its base. If the damage was found sufficient to put the aircraft out of control, it was further assessed in terms of the time that would be required for control to be lost. The six categories of aircraft kill thus established were given code letters (KK, K, A, B, C, and E) for easy reference.

Sources of Aircraft Vulnerability Data. The principal sources of the data used in aircraft vulnerability analysis were theoretical studies, flight operations (including combat rounds), and test firings. The first of these consisted of aerodynamic studies, duel and war game theories, theories of projectile, blast, and fragment performance, and wound ballistics (together with formulas for the reduction of such data to quantitative form for analytical use).

Flight records, especially combat records, had distinct limitations for use in aircraft vulnerability studies, chiefly because they generally did not contain the types of information needed.

In general, test firings and proving ground experiments produced the majority of data on which aircraft vulnerability studies depended. In all, more than a thousand aircraft, most of them obsolete, were used to get the needed information. As complete planes were broken down into components, they were fired upon on the ground or suspended between towers; a wide variety of ammunition, including both blast and fragmentation types, was employed. The damage inflicted was assessed by specialists who examined the target carefully after each hit and recorded their opinions of the probability that the component hit was damaged sufficiently to cause the type of kill being investigated. In many instances replica targets were used in place of actual aircraft components.

To compare the vulnerability of a component of one aircraft type to a given weapon with that of the same component of another aircraft type to the same weapon, and to compare the vulnerability of one component to another component of the same aircraft, the concept of vulnerable area was used. Vulnerable area, expressed in square feet, was obtained by multiplying the presented area of a component by the probability-of-kill factor established for a given weapon for a specific angle of attack.

The Utilization of Aircraft Vulnerability Data. The data obtained by these methods were variously employed. First they served as a guide to aircraft designers in devising passive defense measures to incorporate in new combat aircraft. BRL had neither the authority nor the responsibility for recommending that such measures be adopted; all it did was to make available the information and conclusions it produced. Secondly, the data were used in evaluating the effectiveness of the different weapons used against aircraft and to assist in designing and developing improved models. Finally, aircraft vulnerability data, together with other data obtained from weapons effectiveness analyses, were used to predict the outcome of engagements between two aircraft (a fighter and a bomber, for example) with specified performance characteristics, armament, and passive defense measures; they also were used in comparable analyses of engagements between combat formations of aircraft. BRL developed mathematical models for use in such studies, basing their designs on the theory of games.

Aircraft Vulnerability Conferences. So that work done on aircraft vulnerability by agencies in the United States, the United Kingdom, and Canada could be coordinated and the findings of each agency made available to all, the practice of holding both Joint and Combined conferences on aircraft vulnerability was initiated by BRL in 1948. The meetings called for this purpose were of three types: working conferences (of which five were held from 1948 to 1956), ad hoc symposia on either general aircraft vulnerability or some specific problem thereof, and Combined Conferences, held alternately in England and the United States approximately every eighteen months (the first Combined Conference met in England in May-June 1949). By these means close cooperation of the interested agencies was assured at all levels.

Studies of the Vulnerability of Armored Vehicles. The rapid rise of armor to the position of a major combat arm in World War II placed a premium on

vulnerability studies of armored vehicles as a means of giving them greater protection against the weapons used against them, and also made it essential that the information gained be used to increase the destructive power of U.S. antitank weapons. Russia's emphasis on the continuing development and utilization of armored vehicles and antitank weapons throughout the postwar period underscored the need for carrying out such studies as far and as rapidly as possible.

A number of armor vulnerability investigations were conducted during and just after the war, but it was not until the latter part of 1948 that a program was initiated for systematic study of the vulnerability of armored vehicles. The objectives of this program were the gathering and analysis of data about combat vehicles to be used to increase their combat effectiveness and to design antitank weapons of increased destructive power. Technical supervision of this program was originally assigned to Watertown Arsenal, where the initial investigations were directed toward determining by firing tests the performance characteristics of AP, APC, and HVAP shot against armor plate of various types and arrangements. The findings of these studies demonstrated conclusively that the overall program was extremely broad in scope and complex as well. Because BRL had personnel with qualifications for handling such a research program and experience gained in work in the aircraft vulnerability program, technical supervision was transferred to BRL in April 1949.

After making a complete survey of the literature dealing with all aspects of the overall problem of armor vulnerability and reviewing all programs and projects of a generally similar nature, wherever conducted, BRL initiated studies to analyze all possible measures by which a tank could be put out of action or otherwise prevented from completing its offensive mission; each antitank weapon investigated was evaluated for effectiveness in terms of the different kinds of attack it could be used for. Parallel studies were planned to determine the type and degree of protection that would be required to defeat each antitank weapon. This second phase of the program called for evaluation of all protective factors such as the characteristics and arrangement of armor, the armament and maneuverability of armored vehicles, and the employment of armored vehicles in groups. The results of all these studies were to be made available to those responsible for the design of improved armored vehicles and antitank weapons.

From the beginning of the work on this program, it was apparent to BRL that available data on armored vehicle vulnerability were quite inadequate for the research task to be performed; also, that procedures for the effective evaluation of data were needed. The experience gained in the aircraft vulnerability program was invaluable in solving these problems.

Development of Procedure. One of the first steps was to determine as accurately as possible the range at which the majority of engagements involving armored vehicles took place. Records of tank combat were analyzed and a great variety of topographic maps were studied. It was concluded that, in general, tanks were fired on and opened fire as soon as they or their targets could be seen; apparently range as such was only a minor factor in the opening of engagements involving armor. The deciding factor was terrain, including the location and extent of woods, if any.

Combat data from World War II also were analyzed to determine the typical distribution of hits on Allied tanks, whether or not the vehicles were put out of action by the damage. The information was then used to determine the directions of attack that the enemy had most commonly used. The findings were of great value in deciding how much armor a tank needed and where it could best be placed to reduce the vehicle's vulnerability to antitank weapons.

Once the frequency distribution of hits and the relative positions of U.S. and enemy tanks in normal combat had been calculated, the next step was to determine the probability that a tank would be hit in combat. To do this, the performance characteristics and terminal ballistic data for the various antitank rounds, supplemented by the results of special tests, were analyzed. Many studies of tank engagements conducted by the Army Field Forces, in which engagements range finders were used or not used, as planned, were employed in this phase of the work. Still other studies dealing with the accuracy of shoulder-fired weapons used against tanks were also used. The

data from all these sources were then combined in different ways to obtain estimates of hit probability that could be relied upon for different situations.

The next problem was that of estimating the time required to obtain a first-round hit, once an enemy target had been sighted. In 1952 Project Stalk was carried out for this purpose; the guns of several contemporary U.S. tanks were used as test weapons. Work on this problem was continued for two years at Camp Irwin, California, under BRL supervision and with support from many different Army organizations. For example, many tests were conducted to compare different tanks and their fire control systems under simulated combat conditions in which rapid rate of accurate fire was essential to survival.

From the information obtained by Project Stalk it was found that the time needed, from the sighting of an enemy target to obtaining a first-round hit, did not vary among the tanks and crews tested at the ranges used (which were from 500 to 2,000 yards). On the other hand, this time interval increased appreciably for all cases as the range was increased. Use of a range finder did not materially reduce it at any range. Intensified training of tank crews reduced the time interval between sighting an enemy target and the opening of fire, but did not increase the probability of obtaining a first-round hit or reduce the average number of rounds fired before a hit was made.

Though the information provided by Project Stalk was valuable, it did not cover such points as the probability that a hit would kill a tank, or the ability of an enemy tank to defend itself by knocking out an attacking U.S. tank before the enemy tank was hit.

Once the probability of first-round hit was determined, the next step was to calculate the probability that, assuming a hit, the projectile would perforate the vehicle's armor and do crippling damage inside. When work began on this phase of the program, a considerable quantity of data on the penetration capabilities of kinetic energy and HEAT rounds were available. Additional tests provided data on the spalling capabilities of HEP (High Explosive Plastic) rounds and supplemented the data on kinetic-energy and HEAT rounds already on hand. Grid screens for marking off each presented face of a tank or self-propelled gun were then devised; also, assessment procedures were developed for estimating the probability that a hit on any one section would kill a vehicle. Three categories of kill were established: K (destruction of the vehicle or damage sufficient to render it useless as a weapon), M (loss of mobility and maneuverability), and F (loss of fire power for either offensive or defensive purposes).

The necessary statistical procedures by which the data gathered for each step of the overall procedure could be reduced to usable form were carefully refined, so that studies of armored vehicle vulnerability could be made on a sound and relatively complete basis.

The Test Program. The empirical data required for determining the vulnerability of armored vehicles were obtained by test firings at Aberdeen Proving Ground; the damage done by each hit was assessed by officers with combat experience in armored warfare. The information thus gathered and evaluated for specific tanks was reduced to a form which enabled it to be used in estimating the vulnerability of other tanks and self-propelled guns, whether in service or still in the design or development stage. Detailed probabilities of kill by specific rounds were calculated for the Russian T34/85 and JS-3 tanks and the United States M47, M48, and T-95 series tanks.

Once this detailed analysis was done, the possible effects on vulnerability of varying such features as the caliber and velocity of a tank's main armament, the horsepower of its engines, and the thickness and arrangement of its armor could be investigated. For this purpose, simple empirical formulas were developed. Another approach to the problem of vulnerability was to consider the distribution of the antitank weapons in enemy divisions to estimate the probable fire power that could be effectively directed against U.S. armored vehicles in combat; the information obtained by such means also provided a basis for choosing the antitank weapons to be used against enemy armor. Such studies were conducted to determine the best combination of the design features and numbers of armored vehicles needed to inflict maximum damage on an enemy for a given price of the loss of U.S. vehicles and weapons.

The data gathered by these various means made possible the development of tank battle models; the computations for these models were made on the ORDVAC.

The Passive Defense of Armored Vehicles. One very important phase of the program for determining the vulnerability of armored vehicles, as carried out by BRL, was the study and recommendation of passive defense design features by which the vulnerability of armored vehicles to different types of ammunition could be reduced. This involved consideration of such factors as thickness, slope, and materials of the armor to be used, the design of turrets, and the arrangement of components and personnel within an armored vehicle. The recommendations for changes or innovations indicated as useful by tests were submitted for consideration to the designers of armored vehicles.

Tank Vulnerability Conferences. A series of five tank conferences, beginning in 1950, were held by BRL to keep all interested agencies informed of the progress of research and development work and to provide opportunity for discussion of the more critical and significant points by the men best qualified to consider them. Representatives of Army, Navy, and Air Force organizations and agencies of the United States, the United Kingdom, and Canada attended these conferences, bringing to them the best knowledge of their respective countries and services in this highly specialized field. These conferences proved valuable in advancing the techniques for analyzing the vulnerability of armored vehicles to ordnance weapons.

Studies of the Vulnerability of Ground Targets. During 1956 a systematic investigation of the vulnerability of ground targets to aircraft guns and rockets was conducted. Before this program was initiated, scattered data based on small-sample firing tests had been accumulated, but no concerted effort had been made to study the vulnerability of ground targets to such aircraft weapons. The major emphasis was placed on determining the vulnerability of Army trucks to fragments of known mass (from 11 to 240 grains) and striking velocities (from 2,000 to 5,000 fps); the immediate objective was assessed as either critical (vehicle was stopped within five minutes of being hit) or intermediate (vehicle ran for more than five minutes after being hit but was stopped within one hour). Although the data gathered were not sufficient for making complete analyses of truck vulnerability to such missiles, enough was learned to indicate a definite relationship between striking velocity and mass of a missile, on the one hand, and critical damage, on the other.

Other ground targets for which similar studies were planned included AA gun emplacements, radar installations, locomotives, personnel, and some munitions. Work on personnel was the most advanced. The Office of Ordnance Research furnished the Weapon Systems Laboratory with data on the presented area of standing and prone soldiers on level ground and crouching soldiers in trenches; these data were given as functions of fragment attack angle.

Studies of the Vulnerability of the Continental United States to Aerial Attack. In connection with the inter-service program for the air defense of CONUS, but not as an integral part of it, in 1952 BRL initiated a study of the vulnerability of CONUS to enemy air attack, with special emphasis on the feasibility, effectiveness, and cost of a Nike guided missile defense. The study indicated that from two to eight million people could be killed by a nuclear bomb attack, and most of the casualties would occur in from five to ten of the largest cities.

As a countermeasure against such attacks, the defense of a given area (for example, a major city) was planned to consist of rings of guided missile, rocket, and AA-gun installations around the area. It was assumed that each of these weapons would be most effective against single bombers (that is, an individual bomber that was not flying in formation). Various combat situations were also assumed, and a preliminary mathematical model for the air defense problem thus posed was developed.

From the findings of this study it was estimated that a defense of the type defined, based on guided missiles as the principal defensive weapon, could reduce casualties by two-thirds and would cost approximately $520,000,000. At a slight increase of costs it would be possible to add a battery to fire

large-warhead guided missiles, which could disrupt enemy formations and spread out the bombers in such a way that they could be effectively engaged by the smaller-warhead missiles.

EVALUATION OF WEAPON SYSTEMS

An enormous amount of work was devoted to this phase of BRL's research activities, so that it would be neither practical nor desirable to attempt to describe it in detail. Accordingly, only the character and scope of the weapon and weapons systems evaluations that were conducted in each of these four categories will be discussed. For convenience, ordnance weapons generally were classified as surface-to-surface, surface-to-air, air-to-air, and air-to-ground for the purpose of determining their effectiveness in the performance of missions for which they were designed.

Surface-to-Surface Weapons. Evaluations of the weapons employed by ground forces against enemy ground forces were made during World War II and work to this end was intensified after V-J Day. When reports from Korea indicated that fragmentation projectiles were causing some 80 percent of U.S. casualties, major emphais was placed on the evaluation of such weapon-ammunition systems as guns, howitzers, mortars, and rockets firing fragmentation projectiles under a wide variety of conditions (air and ground burst, various angles of fall, different types of protecting cover employed by target troops, etc.). From these studies came many recommendations for improving both weapons and the rounds they fired; the development of multi-walled fragmentation projectiles was a good example of one of the results obtained. The detailed analyses of such factors as the angular distribution, density, and velocity of fragments that were required in these studies would not have been possible without the electronic computers BRL acquired after the war.

One of the major weapons evaluation programs BRL conducted in the ground-to-ground category was concerned with field artillery pieces and their ammunition. It was initiated after a Combined Conference on Field Artillery held at Fort Monroe in 1949 established military characteristics for the new towed light and medium howitzers and heavy gun desired for Combined use. Attention was directed toward such problems as the accuracy and terminal effectiveness of projectiles, characteristics of the cannon, mobility of the piece, and range. Intensive studies conducted by BRL involved fuzing, costs of producing both the weapons and their ammunition, optimum tactical employment of each cannon-ammunition combination, vulnerability of the weapon to fragments and blast, maximum lethal areas attainable, and the comparative effectiveness of different pieces per pound of ammunition fired. One conclusion was that the most desirable towed howitzer was one that fired the largest round of fixed ammunition that could be loaded by one man (such a round would be approximately 50 pounds in weight). It was also concluded that such a towed howitzer (with a caliber of approximately 115 mm), with proper ammunition, would be able to perform all the missions of a larger (medium) howitzer. This view, which, if accepted, would have deleted towed medium howitzers from the list of weapons to be developed, was not adopted.

This program for evaluating towed field artillery cannon-weapon combinations served as a pattern for similar research programs for mortars, small arms and hand grenades. The evaluation of ground-to-ground weapons continued throughout the 1950's.

Surface-to-Air Weapons. After 1946 BRL maintained a comprehensive program for determining the desirable and attainable characteristics to be incorporated in the weapons used against enemy aircraft. The analytical procedure developed for determining the desirable and attainable characteristics to be incorporated in weapons used against enemy aircraft was more complex than the one developed for the evaluation of ground-to-ground weapons. Loki, Hawk, and Nike, all AA guided missiles, were compared in effectiveness against single bombers, with each other, and with a 60-mm AA gun and a 70-mm AA boosted rocket. The kill probability of each weapon against selected Russian and American bombers was determined as a function of the altitude of the target. The same weapons were comparatively evaluated for defense of a field army against the

same aircraft attacking in formation. Much of the information obtained was valuable to the program for the air defense of CONUS.

In connection with the evaluation of ground-to-air weapons as such, much attention was given to the fire control systems on which such weapons depended. A program termed the Dynamic Tester Program was initiated jointly by the Army Field Forces and the Ordnance Corps to develop a system for the dynamic testing of fire control systems for AA guns and guided missiles.

Air-to-Air Weapons. As noted at the beginning of this chapter, the real beginning of the aircraft vulnerability program, which necessarily included an enormous amount of work for determining the effectiveness of air-to-air weapons, was the optimum caliber program for aircraft guns initiated in 1945. Because so much of what was done from 1945 to 1956 to evaluate air-to-air weapons has been described in the section on aircraft vulnerability, discussion here would be repetitious.

Air-to-Ground Weapons. Because many aircraft guns and rockets, if mounted on night-intruder bombers, fighters, or fighter-bombers, were used against ground as well as aircraft targets, they had to be evaluated for both purposes. In addition, aircraft bombs constituted a major category of air-to-ground weapons.

In evaluating aircraft guns and rockets as air-to-ground weapons, attention was given to effectiveness per pound per weapon installation and the cost per unit of ammunition delivered against a target. The effects of enemy counterfire and of the cover shielding different types of target also had to be taken into account. The data required were obtained for the most part from the different fields of ballistic research conducted by BRL.

For many years BRL maintained projects for determining the effectiveness of aircraft bombs. In 1949, for example, it issued a comprehensive report which recommended a series of new bombs to the Bomb Requirements Board of the Air Force. These recommendations were based on thorough analysis of such bomb characteristics as gross weight, weight and type of filler, aerodynamic shape, and terminal ballistic performance. One significant recommendation was to reduce the variety and sizes of bombs to the minimum consistent with effective attack; in this connection the productive capacity of American industry was given careful consideration.

Ballistic Design Studies for Guided Missile Warheads. As the development of guided missiles was accelerated and the new weapon assumed an ever-increasing importance to future warfare, BRL conducted a number of ballistic design studies for both Army and Air Force guided missiles. These included investigations of blast-fragmentation, continuous-rod, shaped charge, and cluster-type warheads. In each study the relative effectiveness of different explosives for the particular purpose at hand was determined, and attention was given to special problems such as controlling fragmentation.

The Ballistic Research Laboratories were frequently called upon to solve engineering problems outside the research field but which nevertheless dealt with the design and operation of ordnance materiel. The work done in compliance with these requests included kinematic analyses of guns, investigations of recoil systems, studies of electric primers, and studies of other factors that affected the performance of weapons.

An enormous number of weapons were so analyzed after the second World War; therefore only a few examples are used to indicate the type of work BRL did in this field and to show the extent to which this work eliminated causes of malfunctioning and below-standard performances of armament items that were in service.

INSTRUMENTATION

In ordnance engineering work extensive use was made of many of the instruments that have already been described. For example, drum cameras with appropriate optical-mechanical equipment were used to obtain displacement-time records of the motion of machine-gun mechanisms during firing. Piezoelectric gauges and cathode-ray oscillographs were employed to measure the forces acting on gun trunnions. Strain pressure gauges and cathode-ray oscillographs measured the pressures generated in gun chambers by burning propellants. Solenoid coils and cathode-ray oscillographs recorded velocities and rates of fire. Three- and five-wire ballistic pendulums were used to determine the momentum of moving objects, especially small-arms bullets.

In addition other instruments were developed for specific ordnance engineering purposes. One of these was a beam-scale device that used flexures instead of knife edges to determine the center of gravity of an irregularly-shaped object. This instrument had two definite advantages over the knife-edge type. Whereas the latter device had to be adjusted and oriented before each reading was taken and the knife edges had to be sharpened frequently, the flexure-type beam scale needed no adjustment during measurement other than the leveling of the beam. Another device developed by BRL was a special gun-mount which could be adjusted for the different types of guns to be tested.

KINEMATIC ANALYSIS OF GUNS

BRL analyzed almost every type of gun to study the motions imparted to its various components during firing. The data obtained were used primarily to determine the causes of variation in performance and to provide the basis for suggested changes in design to improve the gun. Most of these studies were concerned with aircraft guns, chiefly because of the complex problem of perfecting armament with suitable recoil systems, a high degree of stability, and sufficiently high rates of accurate fire without excessively increasing the size and weight.

Aircraft Guns. One of the first complete kinematic analyses of aircraft guns made after World War II was that of the M2 caliber .50 Browning machine gun. From the results of this and other similar studies, a method was developed to determine the forces transmitted to the back plate and other components by the moving parts of the gun during a given interval of time. These data, together with the results of theoretical studies, made it possible to determine the frictional forces inherent in automatic operation. They were also useful in evaluating the operation of the components of the recoil system.

A similar study was made of the M3 20-mm gun by firing two types of projectile in comparative tests to determine the pressures, velocities, and forces at the trunnions, and displacement-time records.

By far the greatest part of BRL's work in this field was devoted to the systematic analysis of the recoil systems of aircraft guns. Out of it came the development of the *soft-recoil* system, which had been suggested by Kent in the late 1930's. One of the first such systems was the result of work done in developing and testing a spring recoil system that would reduce the recoil forces of the M24A1 20-mm aircraft gun. Aerial firings of guns using the system demonstrated its superior performance characteristics when compared to all the others available. The findings of this development were then applied in investigations conducted to obtain data to be used in developing soft recoil systems for the T121 30-mm gun for B-47 and B-52 aircraft and the T130/160 caliber 60/20-mm guns.

Both of these recoil systems performed satisfactorily under normal temperature conditions and at all angles of elevation. However, when it was found that the ring-spring assembly originally used was subject to excessive friction at subzero temperatures, additional studies were conducted. These showed that another type of ring spring performed acceptably at low temperatures.

Although the T121 30-mm gun with this soft recoil system performed satisfactorily in the B-47 and B-52 bombers, the gun had a comparatively low (2,000 fps) muzzle velocity. The demand for a higher-velocity gun resulted in the development of the T182 30-mm gun, with a muzzle velocity of 2,700 fps. When fired, this gun subjected the trunnions of its mount to much more severe forces than did the T130 weapon. In response to a request by the Air Force, the Office, Chief of Ordnance, directed BRL to investigate the problem.

Studies were carried out to obtain data that BRL used to design a new recoil system that subjected the trunnions to forces less severe than those produced even by the low-powered T130. This recoil system was service-tested by the Air Force and found to be satisfactory.

In addition to the analysis and design of recoil systems for aircraft guns, examinations were made of failures of feed mechanisms for automatic guns. For example, when it was discovered that the M24A1 aircraft gun failed to feed properly, BRL analyzed the weapon. The input and output torque and voltage of the electrically-driven feed winder and the movement of the gun components were recorded for various rates of fire. The results indicated that, by modifying the feed winder to increase its output speed and slip torque, the feed mechanism could be made to work properly. When these changes were made, additional tests were conducted, and the results showed that ammunition was fed to the gun satisfactorily.

Analyses were sometimes made of foreign weapons. An example of this was the study of the German Mk 103 30-mm aircraft gun to determine the weight of its various parts, its muzzle velocity, trunnion reactions, displacements of the parts of the gun mechanisms, and cyclic rate. One of the chief reasons for examining this gun was that it employed a mechanical friction brake. The gun was larger than most guns that had a simple spring recoil system but was smaller than others of comparable caliber that were equipped with hydraulic recoil systems. Because the mechnical friction brake was not generally used in this country, it was decided to investigate its operation in conjunction with other tests. Although no direct benefits came from this study, it was an example of the many experiments conducted to keep abreast of developments not only in U.S. ordnance but of those in foreign nations as well.

Artillery Guns and Howitzers. Artillery weapons were also frequently analyzed. In late 1946, for example, tests were made of the T37 37-mm antiaircraft gun to obtain data that could be used to improve the rear buffer assembly, which had been found too weak in construction to function properly. Strain gauges and drum cameras recorded the motion of the tube and bolt slide and other moving parts of the weapon. Displacement-time curves were prepared and the information was utilized to improve the assembly.

Another study concerned the shortcomings of the T98E1 105-mm self-propelled howitzer (later the M49 howitzer mounted on the M52 self-propelled carriage). In firing tests of this weapon it was found that the recoil cylinder pressures were not uniform, the buffer offered insufficient resistance during the counterrecoil stroke, and the total time for each recoil-counterrecoil cycle was too short; these conditions caused the howitzer to return to battery with excessive shock. These problems were investigated and the findings were used to recommend modifications in the recoil system. The proposed changes were made and new tests showed that the modified system functioned satisfactorily.

Other investigations of artillery weapons were conducted to find ways of eliminating case ejection difficulties encountered in various tank guns and to improve the rotating bands of the APC, HVAP, and HE-T projectiles fired in the T5E2 tank gun.

Small Arms. Although the number of kinematic analyses of small arms was not nearly so great as those of aircraft guns and artillery weapons, some of the work done by BRL in this field should be mentioned. The T17E5 caliber .60 machine gun, designed for short-range antiaircraft use, was

analyzed to obtain pressure-time and velocity-time curves for the standard-length barrel. Studies were made of the motion of the barrel, receiver, bolt head, bolt body, and also the horizontal trunnion reactions. As a result of this investigation, minor changes were recommended which, when applied, improved the functioning of the weapon.

Also, during the mid-1950's BRL conducted a number of studies of shoulder-fired weapons to determine the effects of their recoil on accuracy of fire. Estimates of the various forces, velocities, and displacements that occurred during firing were made and their effects on the accuracy of the weapon were determined. The results of these studies were used in the design of infantry rifles.

HYDRODYNAMICS OF RECOIL SYSTEMS

Examination of the data obtained in recoil system studies of artillery guns and howitzers indicated that the performance of any given recoil mechanism depended largely on the designer's ability to predict or estimate, on the basis of past experience, the value of the orifice coefficient. It was obvious that this procedure could not take into consideration new or unexpected conditions. In addition, the procedure did not take into account the effects of viscosity and the shape of the orifice. Accordingly, a project was initiated to investigate the influence of such characteristics as viscosity and specific weight of fluid, velocity of flow, and shape of orifice on the value of the orifice coefficient. Sufficient data were compiled from the results of these studies to develop a theory utilizing drag coefficients in the design of recoil systmes.

The initial work was carried out by using a conventional 37-mm recoil system with an annular orifice. When completely developed, the drag coefficient concept provided a very simple means of describing the physical nature of the recoil system. The fluid was at rest and the piston was pulled through the fluid by the recoiling gun, thereby producing drag on the piston. The piston drag was greatly affected by the proximity of the walls; this effect was evaluated by a correction factor determined experimentally.

By use of the drag coefficient and the data obtained in these experiments, the designer of recoil systems could evaluate without difficulty the effects of fluid viscosity and the shape of the orifice without resorting to the successive approximations in design that were necessitated by the application of the orifice coefficient theory.

DYNAMICS OF GUN MOUNTS

In the course of the many theoretical and experimental investigations made of the functioning of various mounts for ground and aircraft machine guns and other small caliber guns, BRL developed analytical methods and test procedures of inestimable value in determining the causes of the various shortcomings of gun mounts. The data so gathered were available to designers of mounts.

Investigations of this type were conducted almost continuously after the end of World War II. One example of the work done in the early part of the period 1946-1956 was the analysis of the M3 20-mm gun on the experimental T118 flexible mount and on the mount then in service use. The two mounts were tested and measurements were made of velocities, cyclic rates, and the forces exerted on the trunnions. Displacement-time curves were prepared for the movement of the belt slide and other components of the gun and mount. These data were then utilized in recommending modifications to improve the stability of mounts of this type.

In the latter part of these ten years much was done to improve the M74 tripod mount. Investigations determined the influence of the weight and configuration of the mount and of the recoil forces on the dispersion of rounds fired in an M1919A4 caliber .30 light machine gun on this mount. The test results were used to modify the mount in order to minimize the rotation of the gun during firing and thus reduce dispersion.

This modified mount, the M74E1, was more stable than the M74 had been, but dispersion of the rounds fired from the gun mounted on it was still greater than desired. Consequently, additional studies were conducted to ascertain the cause of the inaccuracy. The various factors affecting the overturning moment of the tripod were investigated, with special emphasis given to an analysis of the results of the study, recommendations were made for modifications of the recoil mechanism

which, when employed, made the M74E1 mount more stable. Similar studies were made of the mounts for the T121 and T182 30-mm and the T130/160 caliber 60/20-mm aircraft gun.

ELECTRIC PRIMERS

Another BRL contribution to ordnance engineering was the development of the BRL Model No. 3 Synchronizer, a modification of the original firing circuit for guns in B-36 bomber aircraft. The development of this synchronizer was the end-result of investigations carried out to determine the causes of misfires in 20-mm ammunition in the M24 turret guns mounted on the B-36. They had disclosed the fact that the firing circuit then used in the B-36 delivered insufficient energy to the electric primers.

Model No. 3 Synchronizer fired a pair of guns synchronously at a controlled rate by use of a blocking-oscillator, and all primers that were not completely open- or short-circuited would be fired. The new synchronizer was approved for use by the Air Force and was installed in B-36's. In addition to its usefulness in the B-36, the synchronizer also could be employed when synchronized firing was desired in tests on the ground.

Other investigations were carried out to find the causes of misfires in the electrically-primed rounds for the T160E4 and Mk 12 Mod O 20-mm guns and the T145 caliber .60 gun. In each instance BRL suggested modifications of the electrical components which, when applied, improved the gun's performance.

Experiments were conducted with electric primers for use in the Nike and Bomarc guided missiles. In tests to investigate the simultaneous ignition of a bank of 48 electric primers (arranged in parallel) by a single condenser, several banks of primers were ignited by each of three 240-bolt condensers having capacitances of 10, 20, and 30 microfarads. The results indicated that practically no excess energy remained from the 10-microfarad condenser after firing, and only a small excess of energy remained from the 30-microfarad condenser. Several electrical circuits were then checked before successful firing, with the capacitance for each primer varied from 0.6 to 0.7 microfarad. Although the findings from these firing tests indicated that the capacitance required per primer could vary from 0.2 to 0.7 microfarad, it was suggested that the requirement be increased to at least 1 microfarad per primer.

DEVELOPMENT OF IMPROVED PROCEDURES FOR THE SURVEILLANCE OF AMMUNITION

After World War II the Surveillance Section of BRL continued the work that had been so ably begun by Colonel Zornig and Colonel Simon before the U.S. entered the war. Surveillance personnel continued to develop statistical engineering methods, sampling inspection techniques, and grading criteria for the surveillance and quality evaluation of existing ammunition in storage. In addition, they engaged in research in mathematical and experimental statistics for applications to the surveillance of ammunition, ordnance materiel, and certain other ballistic problems.

Problems of Surveillance Resulting from World War II. The advent of nuclear weapons added an element of risk to the storage of ammunition and further complicated the surveillance problem. The principal factor was the great expense involved in producing even small nuclear bombs, which made it impractical of course, to detonate them for grading purposes. Moreover, when hostilities ceased, greater quantities of ammunition than ever before were in ammunition dumps and depots, and complete up-to-date records of their reliability had to be maintained.

Fortunately, while these new problems were multiplying, new developments in the field of mathematical statistics were also in progress, and many of them were quickly applied to solve the surveillance problem.

The Ordnance Statistical Sampling Inspection Tables that had been developed by BRL during the war continued to serve adequately, with improvements and refinements constantly being made. But the need for a table of cumulative binominal probabilities to simplify the calculations involved in large-scale surveillance work was recognized; this was met by the issuance of two reports. The first dealt with a quick method for determining a cumulative binomial probability by making a correction in the corresponding Poisson approximation to the binomial. These tables were available and by these means a few simple calculations sufficed to obtain the necessary figure to three-decimal accuracy. The second report was a tabulation of the most common binomial probabilities, designed for use in constructing double-sampling plans without resorting to separate calculations of the probabilities.

Problems of Surveillance Resulting from the Korean War. As a result of combat reports from Korea, studies concerning the causes of malfunctioning of many ammunition items were intensified. This involved, among other things, the development of special instruments to investigate the causes of malfunctioning, and the design of special experiments to replace surveillance firing tables in as many cases as possible. To complicate the problem, all of the available ammunition was needed for the United Nations forces in Korea, where it was being used up at a much greater rate than it had been in World War II. Because the demand for ammunition was urgent, the rapid grading of ammunition lots was a necessity. For this reason much of the grading of certain types of ammunition, when possible, was done by personnel of the ammunition depots, with the BRL personnel concentrating for the most part on statistical design and the development of appropriate surveillance procedures.

Contributions of BRL in the Field of Statistics. Partly because of the many different problems encountered in surveillance work and the special training many BRL personnel received in solving them, BRL made specific contributions to mathematical statistics. Among these were acceptance sampling, analysis of precision and accuracy, life testing, sensitivity experimentation, in-order statistics, statistical tests of outlying observations, estimation of statistical components of variance, and statistical quality control.

DEVELOPMENT AND APPLICATION OF NEW METHODS FOR THE SURVEILLANCE OF AMMUNITION

Probably BRL's outstanding contribution to surveillance work during the postwar period was the compilation of the extensive and widely-used Table of Cumulative Binomial Probabilities. The need for these tables had been underscored by the extensive computations necessary for the solution

of complex problems during the late 1940's. Dr. Frank Grubbs suggested that they be prepared, and Colonel Simon, while still at Aberdeen, worked closely with him in their compilation, as did Dr. Max Lotkin and others of the Computing Laboratory. The tables were completed in 1952 and were of great value not only in surveillance work but in many other statistical problems.

The values of the cumulative binomial probabilities were computed to 12 decimals and rounded to 7 decimals for final listing. The tables gave cumulative binomial probabilities for sample sizes from 1 to 150 (similar tables prepared by the National Bureau of Standards had a maximum sample size of 50); the probabilities of occurrence of an event in a single trial were given from 0.01 to 0.50 in increments of 0.01. Copies of the tables were made available to other Government agencies and for sale to the public at cost.

After their publication and distribution, supplementary tables were published for the sample sizes that appeared in the original, but also for probabilities of occurrence of an event in a single trial from 0.001 to 0.010 in increments of 0.001.

Also in 1952, largely because of the demands for ammunition for the Korean War, emphasis was placed on the development of improved statistical sampling methods and grading criteria for various ammunition items. The items for which these procedures were prepared included firing devices, ground signals, flash and sound signals, distress signals, high-burst ranging signals, smoke-puff charges, trip flares, double-star aircraft signals, and photoflash cartridges. The actual tests of these items were carried out by personnel of the various depots, but the results were forwarded to BRL for analysis and grading recommendations.

A new problem was posed when the Field Service Division of OCO directed the Ballistic Research Laboratories to grade newly-manufactured ammunition as well as stored ammunition that had previously passed acceptance tests. Difficulties were encountered in carrying out this task because of the difference between acceptance and surveillance standards. However, a program was initiated to establish a standard procedure and inspection plan that could be used for grading both stored ammunition and ammunition that had passed acceptance tests. A committee of representatives of BRL, the Ordnance Ammunition Center, and Picatinny Arsenal was formed to expedite the work. This was established as a long-range program and, although progress was made in resolving the problem, by 1956 the final answer had not yet been found.

Special studies were also conducted to determine the best selection of acceptance numbers in single-sampling inspection plans for attribute inspection, with a fixed sample size. A procedure was developed in which the best selection of acceptance numbers was based on a criterion that minimized the sum of probabilities of errors in grading or classifying lots for specified quality levels. Two methods were developed, one for single-sampling inspection plans for placing a lot in one of two quality categories, and the other for single-sampling inspection plans where a lot could be graded as one of three quality categories. Single-sampling plans for inspection by variables were also studied, using the criterion based on minimizing the sum of risks of errors in grading.

Considerable basic work was done during 1954 in analyzing sensitivity data from *contaminated* populations (employing the method of maximum likelihood) and in determining the first two moments of sampling order statistics from populations that had various percentages of defectives. In the case of order statistics, the tables prepared from the results of the study were very useful and the data they contained could be applied in certain experimental investigations of the Ordnance Corps.

Sensitivity data involving three (rather than two, as had usually been the case) categories of response were produced in terminal ballistic investigations. These data were usually referred to as damage data. In order to analyze them, BRL developed a statistical model that described adequately the three-response problem. By employing the method of maximum likelihood, estimates of the factors and their asymptotic variances and covariances were obtained. Work was also initiated to tabulate the percentage points of the incomplete Beta function ratio (Binomial Probabilities).

During 1954-1955 a group from the Surveillance Branch, headed by Mr. O.P. Bruno, went to Europe to evaluate the reliability of U.S.

ammunition in depots in Germany and France. The group sampled, tested, and analyzed various types of ammunition that varied in caliber from 40-mm to 8 inches, in the European Command.

Other Applications of Surveillance Procedures. From 1946 to 1956 those engaged in surveillance activities at BRL frequently served as consultants for the various Laboratories as well as for other Government agencies, by working on the many different problems arising in connection with the design of experiments and tests, quality control, analysis of sensitivity data, and other fields. Even hospitals made frequent requests for help in establishing quality control methods.

For example, in 1946 a new application of the radial variance technique was made in dealing with the problem of the effects of small arms mounts on the accuracy of such weapons. The recommended procedure was to use a template with concentric rings, in order to determine the average expected firing score and also the amount of the deviation from the average score. Then the effect of the mount on the accuracy of the gun could be determined by firing the same reference ammunition lot in the gun on the mount to be tested.

In 1951, because of the need for accurate fire in the Korean conflict, there was a marked increase in the number of requests from OCO for probability-of-hit data for antitank projectiles, both those in service use and those under development. In response to these requests BRL prepared a great many charts that could be used to obtain quick estimates of the probabilities-of-hit for most antitank rounds.

Other kinds of studies also received considerable attention during this period. In collaboration with the Computing Laboratory, the Surveillance Branch carried out work on the tabulation of the probability distributions for two important sampling statistics. One statistic was the estimate of residual variance based on higher-order differences divided by the estimate of variance based on the usual sum of squares about the sample mean. The probability distribution of the statistic was of importance in the solution of tracking problems, time series studies, and similar investigations. The second statistic was connected with Hotelling's generalized T^2 statistic, which could be applied in analyzing bivariate dispersion patterns for antitank firing; bombing data, dispersion patterns for artillery fire; and other problems of a similar nature.

EXCHANGE OF IDEAS AND INFORMATION

Personnel engaged in work in the surveillance field at BRL maintained close associations with other specialists in the field who worked for other Government agencies and private organizations. In this way ideas and information were exchanged and a better understanding was maintained of the many complex problems encountered in carrying out certain tasks.

One way in which this interchange of information was accomplished was by the establishment of the Ordnance Guided Missile Committee. This committee, containing one BRL representative, was formed in 1952 to coordinate reliability work in Army Ordnance, set up a policy for reliability procedures, and prepare means of solving sampling inspection problems encountered in the guided missile field.

Another committee, composed of representatives of BRL, Picatinny Arsenal, and Jefferson Proving Ground, developed statistically-sound test procedures for evaluating and grading newly manufactured and renovated ammunition lots.

Symposia also were utilized to exchange information in the field. The first Ordnance Symposium on Statistical Methods for Sampling Techniques was held at BRL in November 1953, with representatives of most of the agencies and organizations concerned with such problems in attendance.

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Among the many Governmental and private establishments that contributed to the advances that made the first postwar decade historic in the annals of military technology, the Ballistic Research Laboratories played an influential role. By adding personnel and expanding facilities as new responsibilities were assumed, BRL did much to convert into realities what a decade before were regarded as visionary concepts of ordnance weapons.